EVOLUTION
Why Humans Live So Long

INFOTECH
The Data-Driven Society

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Gravity Waves

The search for the beginning of time

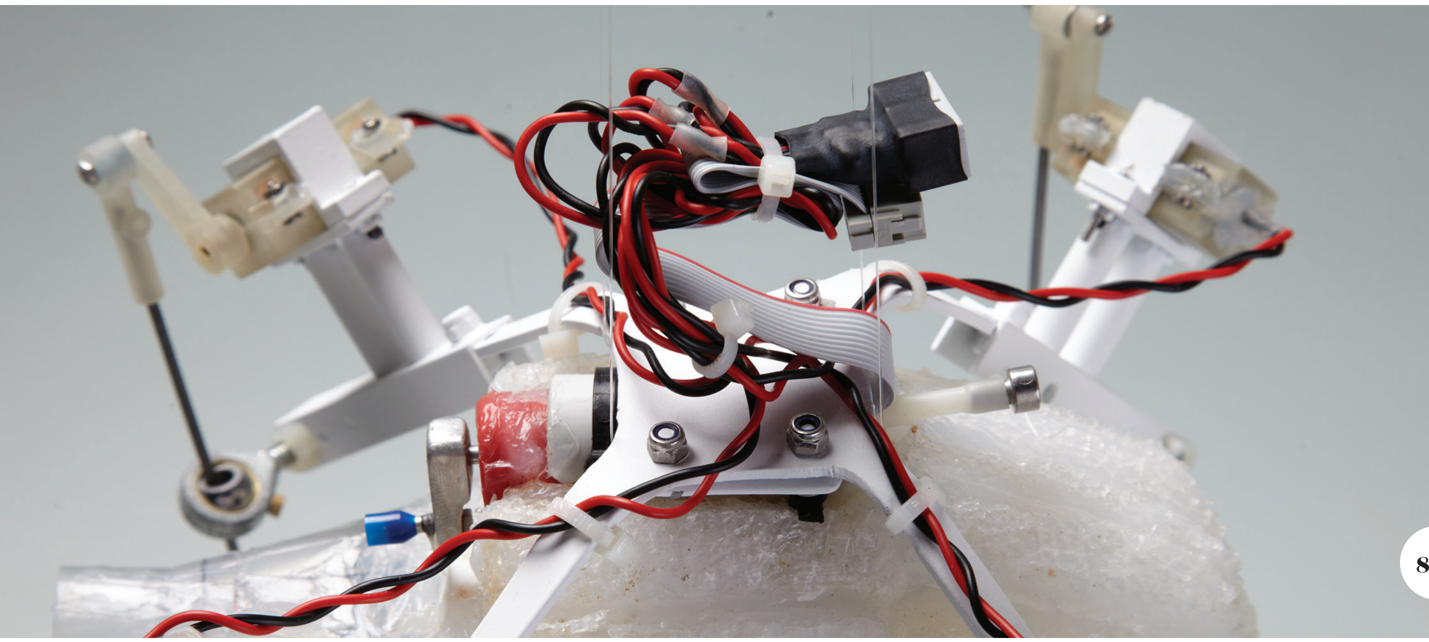
SPECIAL REPORT
2013 State of the World's Science

SCIENTIFIC AMERICAN

October 2013 Volume 309, Number 4

ON THE COVER

Gravitational waves will allow scientists to peer into cosmic voids where ordinary light cannot pass—beyond a black hole's event horizon, for instance, or back to the first trillionths of a second after the big bang. New ideas for gravitational-wave observatories may harken a historic transition into the post-photon era, where gravitons rule. Illustration by Moonrunner Design Ltd.



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Photograph by Reinhard Hunger

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SCIENTIFIC AMERICAN

DEPARTMENTS

ON THE WEB

Who's the (Science) Fairest of Them All?

In September the teenage finalists in the Google Science Fair converged on the company's California headquarters for the awarding of the top prizes. Read about the young scientists whose innovations topped the judges' ballots.
Go to www.ScientificAmerican.com/oct2013/gsf

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Mariette DiChristina is editor in chief of *Scientific American.* Follow her on Twitter @mdichristina

Nexus of Invention

In September 2012, at the annual Meeting of New Champions, or "Summer Davos," in Tianjin, China, I talked to the World Economic Forum (WEF) organizers. At last, they told me, policy leaders and others have come to appreciate that basic research underpins the innovations that nations seek to live sustainably in a finite world. What they don't yet know is how to speak the language.

That is why *Scientific American,* along with our sister title, *Nature,* has been helping identify scientific speakers and topics for the WEF meetings—and why I am particularly excited about a new initiative, the Global Agenda for Science, Technology and Innovation. It was introduced at Davos, Switzerland, this past January and will be further developed at this year's WEF September gathering in Dalian, China. The goal is to announce a set of initiatives at Davos in January 2014.

To get a sense of the complexities of bringing innovations successfully to global markets, turn to page 56 for our second annual "State of the World's Science." The features in the report explore how to foster productive collaborations, how well different nations exploit scientific research and how the situations differ in China and Mexico. SA

AWARDS

Digital Learning

Inspired by our special report in August, "Learning in the Digital Age," *Scientific American* and Macmillan Science and Education (our parent company) held an executive summit at Google's New York City offices with more than 120 attendees. Speakers included policy leaders from the White House's Office of Science and Technology Policy and the U.S. Department of Education; members of academia; and business community innovators.

A highlight for me was giving actor, writer and director Alan Alda (*at right*) a *Scientific American* award for educating the public about science, through such efforts as his 11-year stint hosting *Scientific American Frontiers* on PBS and his teaching scientists how to engage the public at the Alan Alda Center for Communicating Science at Stony Brook University. "There's nobody more passionate about their work than scientists," said Alda, who has pioneered the use of improvisation to help researchers better connect with their audiences. "I read *Scientific American* cover to cover because it's full of wonder," he added. "It just makes me so happy to see smart people's brains at work." Find all the videos of the event by searching "Learning in the Digital Age" on YouTube. —*M.D.*

Photograph by Philip Montgomery, Illustration by Nick Higgins

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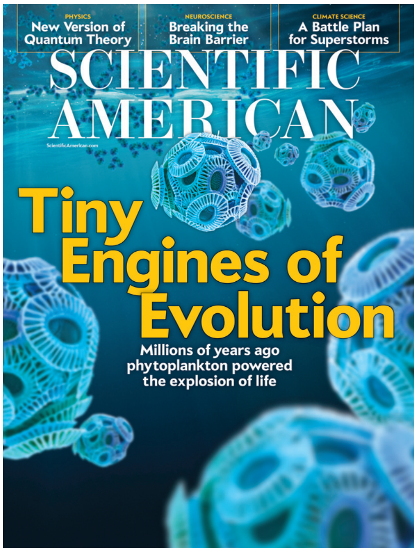

June 2013

QUANTUM WEIRDNESS

In "Quantum Weirdness? It's All in Your Mind," Hans Christian von Baeyer describes quantum Bayesianism (QBism) as a model of quantum mechanics in which the wave function exists only as a mathematical tool employed by an observer to assign his or her personal belief that a quantum system will have a particular property.

But what about the famous two-slit experiment in which the wave function of an electron interferes with the portion of itself going through the other slit? Can my belief about which slit the electron went through interfere with itself?

Gordon Hazen
Northwestern University

Von Baeyer often employs straw men in his criticisms of frequentist probability. For instance, he cites the University of London's Marcus Appleby's example of a lottery won by the same person each week for 10 years. Appleby and von Baeyer ridicule the frequentist who would bet in this lottery in spite of the evidence that it is rigged. Their imaginary frequentist is made to assume that each draw is an independent event, while they afford themselves the luxury of suspecting dependence.

Both frequentists and Bayesians accept independence and use Bayes' law to deal with conditional probabilities. Von Baeyer fails to explore their real differences.

Zachary Miller
Fleetwood, Pa.

"The FDA does not monitor or evaluate so-called medical marijuana. It's smoker beware!"

FIONA McGREGOR *SAN FRANCISCO*

VON BAEYER REPLIES: Hazen is correct that the wave function for a single electron in a two-slit experiment passes through both slits. QBists agree; they differ from other interpreters of quantum mechanics in their insistence that the wave function itself resides only in the agent's mind and that it does not describe the actual path of the electron. It is a calculational device for determining the betting odds the agent should assign for the outcomes of future experiments to detect the electron and is no more substantial than the number on a laundry ticket.

The example I chose to illustrate the difference between Bayesian and frequentist probability, which Miller finds unfair, is perhaps too extreme. Consider instead a series of real coin tosses made by a real person. Ten heads in a row is rare but not unusual. How about a 100, or 1,000, or a million? There is no rational reason to suspect foul play if any of these cases occur because all are possible even under fair conditions. Yet a reasonable person would begin to smell a rat after some (implausible) number of heads. The value of that number differs from observer to observer and is therefore subjective. Frequentism makes no allowance for this normal human behavior, but Bayesianism does.

TABLE TALK

"Cracks in the Periodic Table," by Eric Scerri, is especially interesting for three reasons: the periodic table is often regarded as the symbol of science; the article highlights the problems associated with the current classification approach, which is based on chemical properties of the elements; and, correct me if I am wrong, for the first time since its introduction in 1928, the Janet left-step periodic table is prominently displayed on the pages of a popular scientific magazine.

The periodic system has two levels of classification: a primary level, based on atomic numbers of the elements, and a secondary one, based on chemical properties. Just as imprecise atomic weights were replaced with precise atomic numbers for the primary classification, the loosely defined "chemical properties" should be replaced with more precise characteristics of the elements based on spectroscopic signatures and/or physical attributes of the atoms, such as electron orbitals. The left-step table is the first step in achieving this goal.

Valery Tsimmerman
Brookeville, Md.

Nowadays the Janet left-step table seems to be the favorite of physicists. In that chart, helium is placed above the alkaline earth elements, contrary to its usual position as a member of the noble gases family in conventional tables. It is difficult to see what the chemical similarity between helium and alkaline earth metals is, however. Despite several advantages of the left-step table when compared with the traditional one, I wonder whether adoption of the left-step formulation amounts to putting the cart of quantum mechanics before the horse of chemistry.

Martín Labarca
National Scientific and Technical Research Council and National University of Quilmes, Argentina

SCERRI REPLIES: The left-step periodic table actually has been featured in a magazine article before; I discussed it in some detail in the British magazine Education in Chemistry *in 2005. One might argue, however, over how "popular" that periodical is.*

Labarca's comment serves as an apt response to Tsimmerman's suggestion that the classification of the elements should be based exclusively on, say, electronic configurations. The chemistry of the elements may not be fully reducible to quantum mechanics. If electronic configurations were all that mattered, chemists, physicists and designers of the periodic table would long ago have agreed to the placing of helium among the alkaline earth metals in view of its two electrons in a shell configuration.

The article's discussion of "relativistic" electrons causing certain atoms to behave differently than their position on the peri-

odic table was, in part, intended to illustrate why it is not safe to extrapolate based simply on the number of outer-shell electrons in any atom.

ERRONEOUS EXOPLANET

The June 1963 report of Peter van de Kamp's claim of a planet around Barnard's star—reprinted as "Intro to Exoplanets" in the 50, 100 & 150 Years Ago column, compiled by Daniel C. Schlenoff—is now widely thought to be spurious. Subsequent astronomers could not verify it using the same technique, which involves looking at photographic images to detect a wobble in the position of the star because of a putative planet. It is thought van de Kamp's measurements were subject to systematic problems because of adjustments and modifications made to the telescope that he used. The technique, known as astrometry, is a viable method to detect exoplanets, but it is not an easy one. And at present, it is well outgunned by searches based on detecting Doppler shifts.

Tom R. Marsh
Department of Physics
University of Warwick, England

MEDICAL MARIJUANA

So-called medical marijuana cannot be "prescribed," as is described by Roxanne Khamsi in "Going to Pot" [The Science of Health]. A "recommendation" can be made for it, but no prescription can be given. When licensed doctors prescribe prescription drugs, they know they have passed clinical trials that have been evaluated by the Food and Drug Administration and that their FDA approval came with suitable warnings.

The FDA can also obtain postmarketing reports of adverse effects. This is not true of medical marijuana, which is not monitored or evaluated for mold, pesticides and other toxins. It's smoker beware!

There are two FDA-approved cannabis-based drugs in the U.S.—Marinol and Cesamet—that can be prescribed. The cannabis-based drug Sativex has been approved for particular treatments in the U.K., Canada, Spain and other European countries. It is in FDA trials but has not been yet been approved in the U.S.

Fiona McGregor
San Francisco

LETTERS TO THE EDITOR

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Letters may be edited for length and clarity. We regret that we cannot answer each one. Post a comment on any article at ScientificAmerican.com/oct2013

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Fiddling While the World Warms

Assessments of climate change must come faster and more frequently

This month the Intergovernmental Panel on Climate Change (IPCC), the United Nations–affiliated body that serves as the world's foremost authority on climate science, is scheduled to issue the first installment of its new climate assessment, six years in the making. The massive report, the panel's fifth, is being released in four parts between now and October 2014. It is stuffed with science, woven together by more than 800 scientists. And it is already out-of-date.

Here are a few recent results that you won't find in the new report: A study published last November found that Arctic permafrost is thawing much faster than we thought, an ominous development that could expel massive quantities of the greenhouse gas methane into the atmosphere, accelerating climate change. Ice sheets in Greenland and the Antarctic are also melting faster than anticipated, which could make the IPCC's estimates for sea-level rise read like yesterday's newspaper.

The IPCC reports also won't make use of the latest advances in the models used to predict climate change. In July, Kerry Emanuel of the Massachusetts Institute of Technology updated the computer models used by the IPCC with more fine-grained data about cyclones, revealing that these storms could increase in number, not just intensity, as the current report holds.

The missed opportunities are an inevitable result of the IPCC's laborious review process, as well as the organization's strategy of releasing all its findings at more or less the same time. That approach made sense in the group's early years, when the painstaking work of creating the enormous assessments—culling research, drafting reports, administering reviews and making revisions—established academic and political credibility for an organization attempting to inform public policy with well-supported science. But the process also forces the IPCC to stop considering new results a year or even two years before the assessment comes out, and it may not fully integrate research that is older than that.

Without the latest data, the IPCC, already conservative in its proclamations, tends to underestimate the risks of climate change. And the slow update schedule gives foot-dragging governments cover, as they can always claim that they should wait for the next report to come out before taking action.

The IPCC has to move faster. To do so, it should drop the major assessments. Instead it should issue frequent, tightly focused reports on specific topics, such as sea-level rise, water scarcity and agricultural yields. Such reports would allow it to incorporate science that is only months old rather than years old.

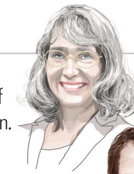
The organization should also conduct its reviews publicly, online. Scientists would post drafts and comments in a wiki-style repository that would grow daily. This format would mute criticisms that the drafting process is overly secretive. Occasional errors, such as a mistake in the 2007 assessment about how rapidly Himalayan glaciers are receding, would be caught right away. Any alleged bias from an author would be revealed. A more transparent system would also help neuter the unfounded (yet enduring) accusations that the IPCC is some sort of political conspiracy, rather than a research review board. Mostly, a wiki approach would ensure that all reports reflect up-to-the-minute science.

Unfortunately, the IPCC is not built to do quick work. The organization currently relies on an army of volunteer scientists encumbered by their day jobs. The group should instead become a permanent, global agency that relies on a nimble, dedicated staff. Institutional models abound, as Eduardo Zorita of the GKSS Research Center in Germany wrote in *Nature* (*Scientific American* is part of Nature Publishing Group): "The European Central Bank, the International Atomic Energy Agency, the International Energy Agency and the U.S. Congressional Budget Office all independently navigate their way through strong political pressures, delivering valuable assessments, advice, reports and forecasts.... These agencies are accountable and respected."

If the IPCC is to maintain its status as the world's most relevant and respected summarizer of climate science, it must evolve. Knowledge moves fast. The rest of the world needs the IPCC to keep up. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/oct2013

Illustration by Michael Glenwood



Eugenie C. Scott is executive director of the National Center for Science Education.

Minda Berbeco is programs and policy director at the center.

Climate in the Classroom

Evolution is not the only scientific idea being kept out of the curriculum

For decades objections to the theory of evolution have bedeviled individual teachers, school boards, state boards of education and state legislatures. Educators fought to keep evolution in science classes and creationism out. We resisted intelligent design, the notion that natural selection alone cannot explain the complexity of life-forms, which served as a way of getting creationism through the back door. We are now fighting legislation that encourages teachers to teach the "evidence against evolution"—facts found only in the creationist literature.

The consequences of antievolutionism are felt in many American schools: evolution is not taught or is taught poorly. Yet evolution is one of the most important ideas in human intellectual history, and students have a right to learn it. The common ancestry of living things and the mechanisms of inheritance explain why things are the way they are. Students and adults deprived of this knowledge are scientifically illiterate and ill prepared for life in a global, competitive world. Students given merely once-over or light instruction in evolution are woefully undereducated.

These "academic freedom" laws are not aimed solely at evolution. They often also take on climate change, another field of science with a body of evidence that is accepted by the scientific community. That the planet is warming and that the burning of fossil fuels over the past 150 years explains the current rapid rate of change are virtually indisputable in the scientific community. But public distrust means that the National Center for Science Education, which formed in the 1980s to contend with antievolutionists, now helps teachers cope with push back on climate, too.

Opposition to climate change stems less from religious ideology than from political and economic ideology. Some political conservatives claim that global warming is a liberal plot to increase the power of the federal government, which if it reduces our reliance on greenhouse gas–producing fossil fuels, will jeopardize national security and threaten our individual freedoms. Some libertarians believe that policies such as carbon taxes are a socialist plot intended to cripple capitalism. True, some political and economic views cannot accommodate policies associated with combating climate change, but we should not let the ideologies of some prevent or distort the education of the many.

The newly released Next Generation Science Standards, developed by a consortium that includes the National Academy of Sciences, 26 states and the nonprofit organization Achieve, will require teachers in states adopting them to teach both evolution and climate change. That does not mean that teachers will necessarily cover these subjects adequately, but in general, in states that adopt the standards students will receive more instruction in evolution and in climate change than they currently do.

The Next Generation Science Standards would deliver instruction that is head and shoulders above what would result from academic freedom acts, which allow for the use of information found only on creationist sites, many of which teach that the earth is not billions of years old, or from climate change contrarian think tanks, which attribute the recent trend in warming not to an increase in greenhouse gases but rather to unstoppable solar cycles. Students would also learn that the pre–industrial revolution Medieval Warming Period refutes anthropogenic global warming—even though it was merely a regional warming event. Scientists do not give these views credence, but that does not keep them from appearing in lesson plans to dispute the fact that human activity has affected the earth's climate.

Today's atmospheric warming rate is not regional; it is global. It affects land, sea and air. The scientific consensus is that humans are mostly responsible. Whatever our society decides to do about climate change, it must be based on solid science. We all will suffer if that science is compromised because of ideological opposition to its consequences. Beginning learners have a right to know what scientists have concluded. It is not right to allow religious, political or economic ideologies to trump instruction in science. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/oct2013

Illustration by Edel Rodriguez

ENVIRONMENT

Coyotes in the Crosswalks? Fuggedaboutit!

The new science of urban ecology reveals a surprising trend of wildlife adapting to the cityscape

Cities are often viewed as environmental wastelands, where only the hardiest of species can eke out an existence. But as scientists in the fledgling field of urban ecology have found, more and more native animals are now adjusting to life on the streets.

Take America's biggest metropolis. As recently as a few decades ago, New York City lacked white-tailed deer, coyotes and wild turkeys, all of which have now established footholds. Harbor seals, herons, peregrine falcons and ospreys have likewise returned in force, and red-tailed hawks have become much more common. Meanwhile the first beaver in more than two centuries turned up in 2007; river otters last year ended a similar exile.

What's happening in New York is by no means an anomaly. Experts say that the adaptation of wildlife to urban areas is ramping up worldwide, in part because cities are turning greener, thanks to pollution controls and an increased emphasis on open space.

In North America, the phenomenon is perhaps best exemplified by the coyote, which colonized cities roughly 15 to 20 years ago. A recent study of the Chicago area found that urban pups had survival rates five times higher than their rural counterparts. "Coyotes can absolutely exist in even the most heavily urbanized part of the city, without a problem," says Stan Gehrt, a wildlife ecologist at Ohio State University. "They learn the traffic patterns, and they learn how stoplights work."

Other studies have found animals from hawks to opossums reaping benefits from urban life. "We need to be careful about thinking of cities as places that don't really have interesting biodiversity," says Seth Magle, director of the Urban Wildlife Institute at the Lincoln Park Zoo in Chicago. "Our urban areas are ecosystems, with just as many complex interactions as the Serengeti or the outback of Australia." *—Jesse Greenspan*

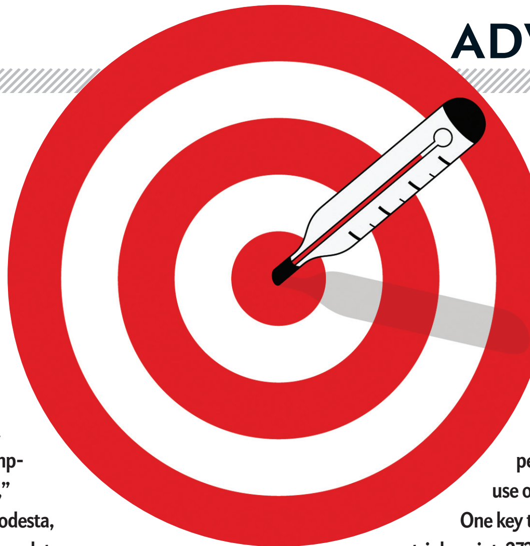
HOWDY, NEIGHBOR: A Chicago coyote, tagged for study

E. JASON WAMBSGANS *Getty Images*

PHYSICS

The Perfect Kelvin

The quest for an absolute temperature scale heats up



The most accurate thermometer in the known universe looks nothing like a thermometer. It is a copper vessel the size of a large cantaloupe, filled with ultrapure argon gas and studded with microphones and microwave antennas. The purpose of the gadget, which sits on the campus of the National Physical Laboratory (NPL) in Teddington, England, is not simply to measure temperature, however. Rather the device and others like it may allow scientists to completely overhaul the concept of temperature and recast it in terms of fundamental physics.

The plan rests on linking temperature to energy via a physical constant. Today the international standard temperature unit, the kelvin, is based on the properties of water, but scientists would like to bring it in line with other measurement units that have been liberated from the vagaries of the macro world. The second is now defined by the oscillations of a cesium atom; the meter relates to the speed of light in a vacuum. "It's bonkers that the kelvin doesn't directly relate temperature to energy," says Michael de Podesta, who leads the research team.

The NPL device measures the Boltzmann constant, which links changes in energy to changes in temperature. De Podesta's team and its competitors hope to nail down the constant well enough to relate one kelvin to a certain number of joules of energy.

The new thermometer—technically an "acoustic resonator"—rings like a bell when the physicists feed certain sound frequencies into its microphones. From that sonic resonance, the researchers can determine the speed of sound within the gas-filled cavity and thus the average speed of the argon molecules—that is, their kinetic energy. In July, de Podesta's team reported in the journal *Metrologia* the most accurate measurement yet of the Boltzmann constant.

The current temperature definition makes use of water's phase changes. One key threshold is the so-called triple point, 273.16 kelvins, where water ice, liquid and vapor can coexist. In 1954 an international agreement defined the kelvin as 1/273.16 the difference between absolute zero and water's triple point.

The 1954 definition works well in general but begins to break down for extreme temperatures, such as those found within stars. "It only happened this way because people started measuring temperature long before they knew what it actually was, before temperature was known to just be atoms and molecules buzzing around," de Podesta remarks. "Now that we know better and have the opportunity to correct it, we should." *—Lee Billings*

COSMOLOGY

Universe Out of Balance

How could the cosmos have become so skewed?

A decade ago cosmologists began to suspect that the universe might be bizarrely lopsided. Hints of a universal imbalance emerged from the afterglow of the big bang, known as the cosmic microwave background, or CMB, which is dotted with hot and cold spots signifying fluctuations in the density of matter. Starting in 2003, data from NASA's Wilkinson Microwave Anisotropy Probe (WMAP) suggested that one side of the cosmos is hotter than the other. But the finding rubbed against the prevailing view in cosmology that the universe expanded titanically during an early growth spurt called inflation, which should have left the CMB looking mostly uniform.

In recent months the case for lopsidedness has gotten much stronger—the European Space Agency's Planck satellite, which is newer and more sensitive than WMAP, has returned similarly reliable evidence of an asymmetric cosmos. The question now is whether the enigma demands a cosmic rethink or whether it results from an extremely unlikely—but ultimately explainable—occurrence.

"After quite a few years of claims based on independent researchers' analyses of publicly available WMAP data, we now have redundancy from Planck as convincing support," says cosmologist Krzysztof Gorski of the NASA Jet Propulsion Laboratory in Pasadena, Calif.

The surprising temperature difference may have become more believable, but it remains a puzzle. Cosmologist Yabebal Fantaye of the University of Oslo, along with Gorski and others, recently ran 10,000 simulations of how the CMB should look, given the Standard Model of the universe's evolution. Only seven outcomes resembled the picture that WMAP has assembled, the researchers reported in *Astrophysical Journal Letters.* In other words, the standard cosmological paradigm can accommodate a lopsided universe but just barely. "It certainly could happen, but it is not very likely," Fantaye says.

Researchers are already exploring the possibility that the asymmetry points to something new—whether hypothetical energy fields warping the newborn universe or ancient bruises from collisions with another universe. Further clues will arrive next year when the Planck team releases data on the polarization of the CMB—the way its photons oscillate—which could distinguish between such cosmological exotica and a mere quirk that fits within the prevailing paradigm. —*Charles Q. Choi*

BY THE NUMBERS

74

Approximate number of yearly deaths from injuries for every 100,000 people in the rural U.S. In the largest American cities the rate is only 50 per 100,000 people.

SOURCE: "SAFETY IN NUMBERS: ARE MAJOR CITIES THE SAFEST PLACE IN THE UNITED STATES?" BY SAGE R. MYERS ET AL., IN *ANNALS OF EMERGENCY MEDICINE.* PUBLISHED ONLINE JULY 25, 2013

COMMENT AT ScientificAmerican.com/oct2013

GEOLOGY

The Holey Land

Monitoring from above predicts sinkholes months before they occur

Sinkholes at the Dead Sea

YUVAL NADEL *Redux Pictures*

Along the shores of the Dead Sea, the solidity of the ground underfoot cannot be taken for granted. In recent years sinkholes, up to 20 meters in depth, have been cropping up at a rapid clip. The collapses have rendered a recreation area unusable and have reportedly trapped a handful of people who required rescue. To get ahead of the problem, a team of scientists identified the signs of an emerging sinkhole from subtle elevation changes in soil. Now they are using those indicators to predict collapses ahead of time.

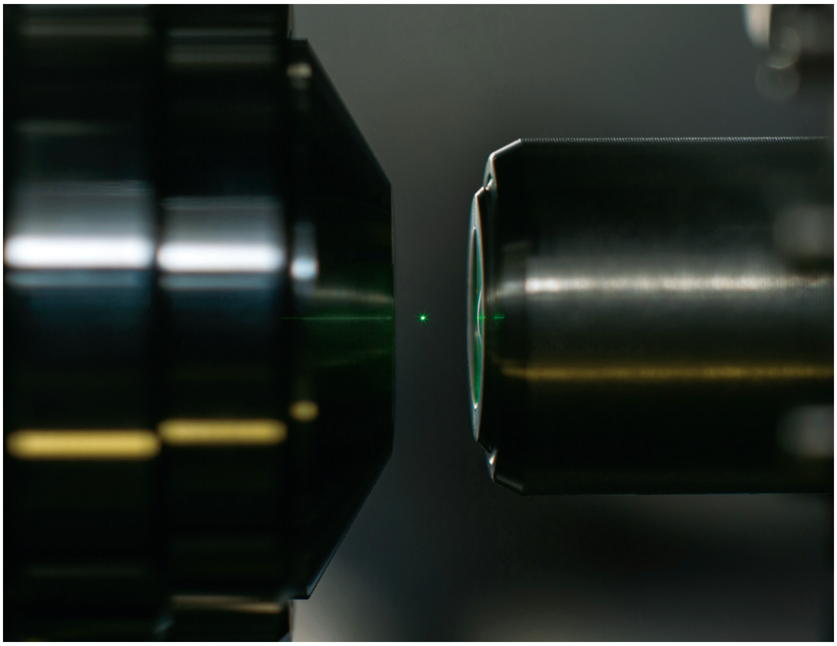
The sinkhole problem stems from the shrinking of the saline Dead Sea, which thousands of years ago deposited thick layers of salt in the soil. Now fresh groundwater has infiltrated areas left dry by the Dead Sea's retreat, dissolving the ancient salt layers and weakening the ground under former lake bed and shoreline.

To spot developing sinkholes, the scientists monitored the region with radar-equipped satellites and laser-ranging aircraft. Meanwhile one researcher paid regular visits to the study area to spot recent sinkholes.

Once new basins opened up, the scientists returned to their data bank to identify subsidence—on the scale of millimeters—in the months leading up to the collapse. The team is using those patterns of emergence to sound the alarm about future collapses. "In one case, we alerted the government, and they designed a road that bypasses the sinkhole area," says study co-author Ran N. Nof, a geophysicist at Tel Aviv University.

It remains to be seen whether the approach would work in Florida and other sinkhole-plagued regions. University of South Florida geologist Timothy Dixon notes that Florida's moist air interferes with radar imagery and encourages vegetation, "which makes it hard to compare one radar image with the next."

—*Arielle Duhaime-Ross*



COURTESY OF J. ADAM FENSTER *University of Rochester*

WHAT IS IT?

Levitating in midair, a fleck of diamond just 100 nanometers across glows brightly in a green laser beam. "This nanodiamond is just suspended in free space, and the way we hold it in place isn't with tweezers or our fingers," says optical physicist Nick Vamivakas of the University of Rochester. Instead Vamivakas and his colleagues use a second laser, with an invisible infrared beam, to produce an electric field that traps the diamond in place.

Nestled inside the specially engineered crystal are hundreds of so-called nitrogen vacancy (NV) centers—nitrogen atoms adjoining gaps in the carbon lattice. The green laser excites the NV centers, which then emit reddish photons by photoluminescence, the team recently reported in *Optics Letters.* The red glow is too faint to see, but the demonstration shows that lasers can manipulate quantum states inside the hovering crystal. Vamivakas says that physicists could even exploit the quirks of quantum mechanics to trap a levitating nanodiamond in two places at once. *—John Matson*

COMMENT AT ScientificAmerican.com/oct2013

GENETICS

Taste-Blind Mice Make Tangled Sperm

Mice missing certain sensory genes wind up with busted gametes

To make healthy sperm, mice must have genes that are well known for a completely different purpose: enabling the sense of taste. It's not as surprising as you might think. Over the past decade biologists have found taste and smell receptors—initially thought to be confined to the mouth and nose—in the brain, the gut, the kidneys and elsewhere throughout the body. What they are doing in all these places is still something of a puzzle, as the sperm study, published in July in the *Proceedings of the National Academy of Sciences USA,* shows.

The serendipitous finding emerged from an experiment that began a few years ago, when Bedrich Mosinger, a taste researcher at the Monell Chemical Senses Center in Philadelphia, was trying to breed mice missing two proteins involved in sensing sweet and umami (savory) flavors. He crossed parents that were each missing one of the proteins, expecting that at least some of the offspring would be missing both. In litter after litter, not a single such mouse was born.

Mystified, Mosinger and his colleagues traced the problem to the male mice by showing that females could pass on genetic material missing the sensory proteins, whereas males could not. "It was very strange and very striking," he says. To explore how the taste-related genes act on sperm, the researchers engineered mice that were missing the gene for one protein, then fed the males a drug that switched off the second gene. Finally, they looked at the animals' sperm—and what they saw was a mess. The sperm heads were bent and often too large, and the tails were twisted over on themselves. By silencing those two taste genes, the researchers had somehow mangled the sperm-making machinery.

Sperm have been shown to host bitter-taste receptors and smell receptors, which most likely sense chemicals released by the egg. But the idea that such proteins might function in sperm development is new, says Yehuda Ben-Shahar of Washington University in St. Louis. In the other cells and organs where taste and smell receptors have been found, usually "the cells mature, and then these things kick in to interact with the environment," he says. "This is the earliest that these types of genes have been implicated in the biological system that I know of."

It is still a mystery how exactly the two genes control sperm development. Elsewhere in the body, researchers have found taste and smell receptors that help to sense toxins, pick up messages from gut bacteria or foil pathogens. At a meeting earlier this year of the Association for Chemoreception Sciences, Ben-Shahar even hosted a symposium entirely devoted to sensory receptors that crop up in unexpected places.

The proliferation of recent discoveries serves as a reminder that a whole world of alternative uses may be out there, even for genes that biologists are sure they have pegged. "When we assign functions to genes, it's a very narrow view of biology," Ben-Shahar says. "Probably for every molecule that we assign a specific function to, if you look hard enough you'll find that it's doing other things in other contexts." —*Veronique Greenwood*

Illustrations by Thomas Fuchs

MEMOIR

The Great Explicator

An appreciation of the legendary Martin Gardner, whose latest work is a posthumous autobiography

In 1956 Martin Gardner invented the perfect job for himself: writing a monthly column called Mathematical Games in the pages of *Scientific American*. Then he invented the Martin Gardner who could do the job. “I hurried at once to the used bookstore section of Manhattan, then near the Village, to buy all the books I could find on recreational math,” he writes in *Undiluted Hocus-Pocus: The Autobiography of Martin Gardner,* recently published by Princeton University Press. “If you look over all my columns…, you’ll find that they steadily become more sophisticated mathematically. That was because I was learning math.”

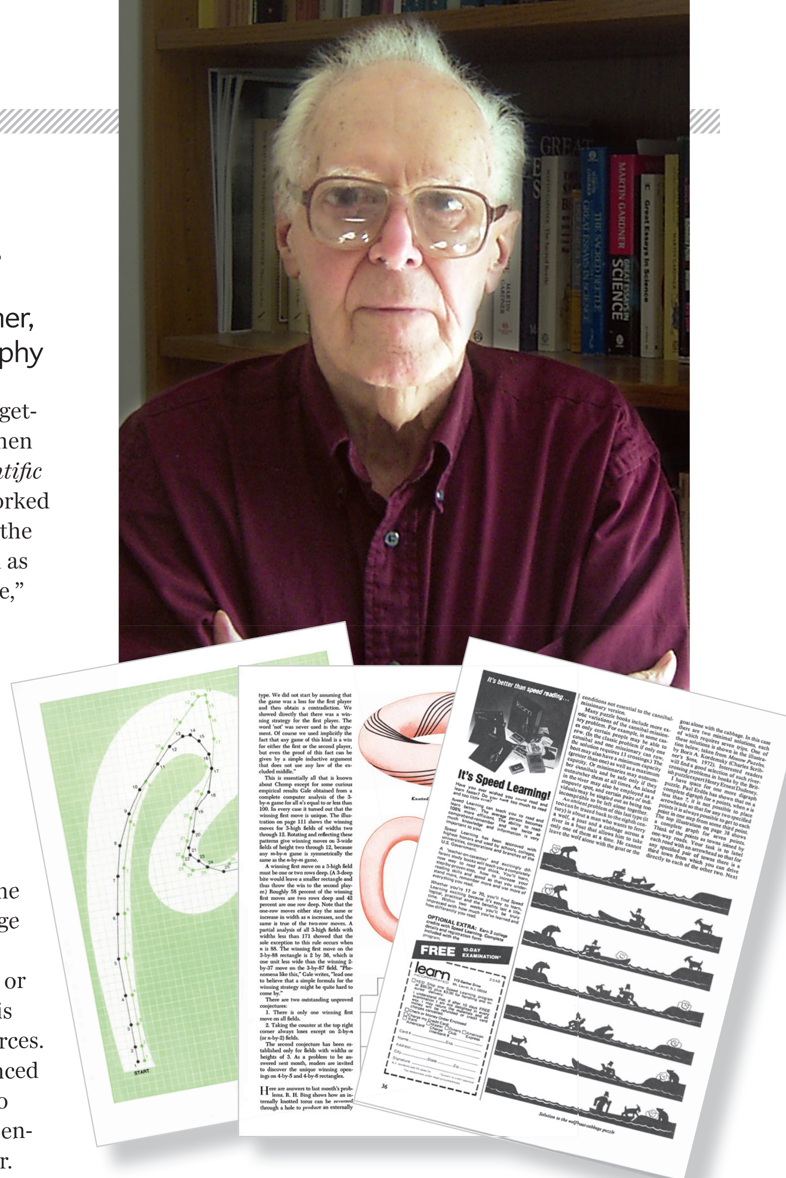
Gardner, who died in 2010 at age 95, presided over Mathematical Games for 25 years, to the delight of millions of readers. Given the title of his column, it’s no surprise that Gardner had a lot to say about games and puzzles. There was fun in every essay—and sometimes even juvenile humor. But he also ventured far beyond the customary territory of “recreational” math. He wrote on the theory of knots, on paradoxes of free will, on learning by induction. He introduced the public to a bevy of big ideas: the nonperiodic tilings of the plane invented by British mathematical physicist Roger Penrose, the fractals of Polish-born mathematician Benoît Mandelbrot and, perhaps most famously, the Game of Life, a minimalist simulation of birth and death devised by British mathematician John Horton Conway.

I had the pleasure of getting to know Gardner when I joined the staff of *Scientific American* in 1973. He worked from home, and around the office we referred to him as a “shy woodland creature,” seldom seen or heard. I might never have met him except that we both lived in towns along the Hudson River, north of New York City, and so I was recruited as a courier of manuscripts. When I visited, he would show me a magic trick, or challenge me with a puzzle (which I usually failed to solve), or deliver the latest from his far-flung network of sources.

When Martin announced in 1980 that he wanted to retire, a delegation of us entreated him to reconsider. We offered him more money, a lighter workload and secretarial help, but our main argument was simply that nothing he might do with the rest of his life could possibly have a greater impact on humanity than continuing the column. Martin did not dispute our point, but he also did not waver in his determination. He wanted to write a big book setting forth his fundamental philosophical and theological principles. That book, *The Whys of a Philosophical Scrivener,* appeared three years later. The *New York Review of Books* published a scathing, dismissive review—written by Gardner himself.

Even now, I still see Gardner’s departure as a waste of human capital, but his autobiography at least makes clear that the decision was no whim. During his tenure as explicator in chief for the world of mathematics, he had other currents flowing through his life. The quarter of a century Gardner spent at *Scientific American* was only about a quarter of his existence, and it gets an even smaller proportion of this autobiography.

The formative event in Gardner’s youth was leaving behind his childhood in Tulsa, Okla., for studies at the University of Chicago, where he majored in philosophy. He told one version of this story in a 1973 novel, *The Flight of Peter Fromm,* which I took for a conventional loss-of-faith narrative: a young man from a fundamentalist Christian family confronts the wider world and leaves behind his illusions. *Undiluted Hocus-Pocus* gives a subtler account. Yes, Gardner turned away from the religion of his parents, but he remained deeply engaged in a quest to find a meaning or purpose in life—and in an afterlife. Atheists have all the best arguments, he concedes, but nonetheless he hopes and believes. —*Brian Hayes*



Martin Gardner’s influential column made him a revered figure within the community of mathematics, but he always insisted that he was a journalist, not a mathematician.

COURTESY OF COLM MULCAHY (*Gardner*); SCIENTIFIC AMERICAN (*pages*)

ADVANCES

EXTINCTION COUNTDOWN

PHILIPPE MICHEL *Getty Images*

Madagascar's Towering Baobab Trees on the Brink

The Ewe people of Togo, among others in Africa, have a proverb: "Wisdom is like a baobab tree; no one individual can embrace it." Indeed, the grand specimens of the genus *Adansonia* can live more than 1,000 years, with trunks 30 feet across.

Six of the world's eight baobab species are found only in Madagascar. But according to a recent study in *Biological Conservation,* climate change and human development will soon erode the habitats of two Madagascan species. One may not survive.

The baobab *A. perrieri* is already scarce—the study's authors spotted only 99 trees in high-resolution satellite images. Because *A. perrieri* is adapted to specific conditions, climate change could shrink its habitat almost 70 percent by 2080. The second species, *A. suarezensis,* boasts a population in the thousands, but its range is small. The tree occupies a very particular rainfall niche, which in a changing climate could force its retreat to just 6.5 square miles of land by 2050. Even worse, *A. suarezensis* may face extinction by 2080. The trees are listed as endangered by the International Union for Conservation of Nature. Now, perhaps, both deserve critically endangered status. *—John R. Platt*

Read twice-weekly updates at blogs.ScientificAmerican.com/extinction-countdown

HEALTH

The Liver Transplant Divide

The map governing who gets an organ transplant favors some regions over others

If you need a liver and live in Boston, your chance of getting one in time is about 53 percent. Drive a couple of hours southwest to Connecticut, and your chances jump to 85 percent.

The difference is encapsulated in the national organ transplant map, which divides the U.S. into self-contained districts of organ allocation. Among other factors, areas with lots of highways—and the accompanying traffic fatalities that make healthy organs available for transplant—will generally have a shorter wait time.

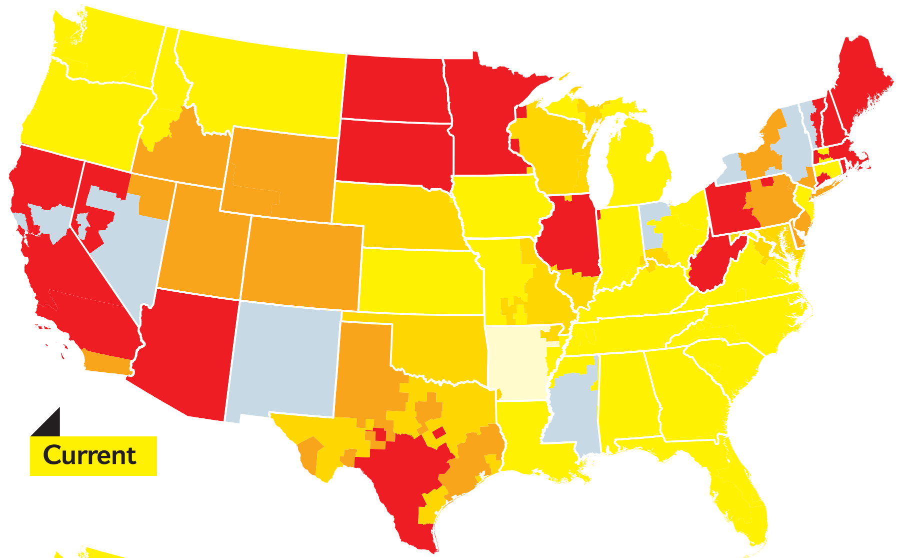
With optimization techniques used to draw political districts, a group of researchers from the Johns Hopkins University School of Medicine has found a potential path to help correct the liver imbalance. The researchers have proposed a redrawn map that levels the odds of receiving a liver throughout the country. A similar approach could possibly help curb inequities for other organs as well.

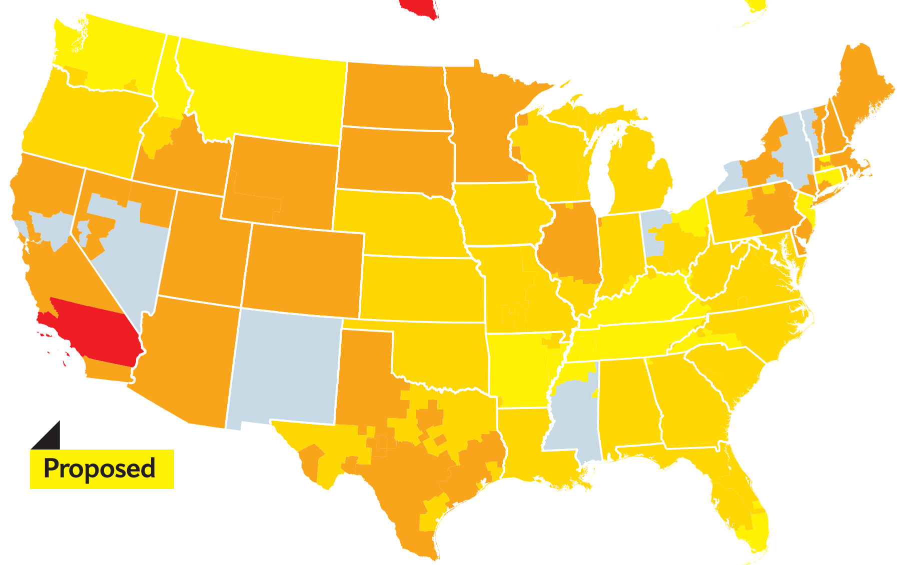
"By using an optimized map, we would be able to cut geographic disparities in liver allocation in half," says study author Dorry Segev, a transplant surgeon at Johns Hopkins. In the name of fairness, some areas' chances would improve, whereas others would fall: a 79 percent chance of receiving a liver before a patient dies in Miami would drop to a 72 percent chance under the new proposal, but in New York City a 56 percent chance would improve to 68 percent. (A host of factors, including a region's organ donation rates, help to shape the odds.)

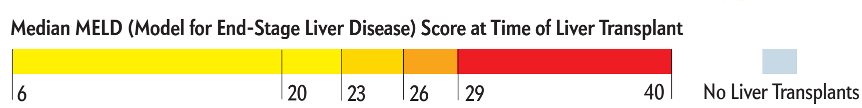
The current donation system, run by the United Network for Organ Sharing (UNOS), offers some recourse to patients in areas with long wait times. Someone in New York City, for instance, can put her name on multiple waiting lists and, if she is healthy enough to travel, can hop on a plane if and when an organ becomes available in Tennessee. Unfortunately, the cost and complexity of long-distance travel, compounded by the logistical obstacles of working with multiple transplant teams, ensure that only 4.4 percent of the almost 16,000 people on the liver transplant list do so.

UNOS says that it is exploring how it could employ Segev's methods, if not his particular map, to tweak its system in the future and better allocate livers throughout the country. The Johns Hopkins team hopes that the liver map will inspire a new distribution system for other vital organs as well. That could truly be some lifesaving technology.

—Dina Fine Maron







Patients secure a spot on the liver transplant list by MELD (Model for End-Stage Liver Disease) score, a snapshot of health that generally ranges from 6 to 40, with 40 indicating the direst cases. Median MELD score at transplant is a proxy for wait time because patients land on the list long before they reach a score of 40. (Hawaii and Alaska are omitted.)

MAPS BY SCIENTIFIC AMERICAN; SOURCE: COREY WICKLIFFE

COMMENT AT ScientificAmerican.com/oct2013

NEUROSCIENCE

Total Recall

Flatworms remember their surroundings, even after being decapitated and growing a new head


Worm's head

The flatworms known as planarians are neuroscience darlings. Their centralized brain, complex sensory abilities and rapid regenerative capacities make these nonparasitic worms ideal for studying the mechanisms that regulate stem cell function, neuronal development and limb regrowth. To this repertoire, scientists have now added a new trick: these invertebrates can store memories outside their brain and retrieve them after losing their head and growing a new one.

Researchers at Tufts University tested the worms' recall by leveraging a quirk of planarian behavior: worms that recognize a familiar locale will settle in to feed more quickly than planarians that find themselves in a new environment. Such newcomers typically need time to explore their surroundings to ensure their safety before they eat. So the researchers introduced planarians to a textured petri dish and allowed them to get acquainted with their environs. Next they decapitated the worms and waited two weeks for their heads to grow back.

The scientists then jogged the worms' memory by briefly returning them to the dish and feeding them. The idea was to revive the dormant memory from the body through a short exposure to familiar turf. "For the worm, automatically imprinting the new brain tissue with an old memory that could end up being completely irrelevant would be a waste," says study co-author Michael Levin, a Tufts developmental biologist. "So the brief exposure tells the brain that the memory is indeed relevant."

When the researchers returned the trained flatworms to the same dish, the planarians initiated feeding much more quickly than worms that had gone through the same routine but had not explored the dish prior to decapitation.

The experiment upholds a controversial, decades-old finding by a colorful neuroscientist named James V. McConnell. In the 1950s and 1960s McConnell performed similar tests on planarians—going as far as to feed bits of trained worms to their untrained brethren in an effort to transfer molecules of memory. But some researchers questioned the objectivity of his experiments, many of which were detailed not in mainstream journals but in his own *Worm Runner's Digest*. The Tufts group aimed to minimize observer bias by using a machine to track and analyze the worms' behavior.

The new research, published in the *Journal of Experimental Biology*, could have implications for the development of artificial memory and the study of neurodegenerative diseases, which researchers hope to treat by someday replacing damaged brain tissue. "We really don't know what that could do to a patient's personality or memories," Levin says. "Planarians are the model that might finally enable us to start looking at that."

—Arielle Duhaime-Ross

TECHNOLOGY

Hackers Crack the iPhone

Antivirus software may not help

Search the App Store for iPhone antivirus software, and you'll find only a handful of security programs. There's a reason that the market is so soft: Apple's stringent app-vetting process and the architecture of iOS products—which partitions, or "sandboxes," code to protect the device—have helped keep iPhones and iPads safe. Sandboxing, which restricts an app's reach, would also limit any antivirus program's effectiveness.

Now researchers at the Georgia Institute of Technology Information Security Center have identified and exploited two weaknesses to infect iPhones. One team disguised phone-hijacking code inside a seemingly benign app, thereby escaping detection by Apple's app reviewers. In the second attack, a team exploited a vulnerable USB connection with an imitation plug-in charger that installs malware.

The researchers alerted Apple to their findings before going public, prompting the company to implement defenses in the new iOS 7. More loopholes are sure to be found. And even if antivirus software were readily available, it might not be able to find or disable malicious code. "When you download an antivirus app, because of sandboxing there are limits to what it can do," says Charlie Miller, a security engineer at Twitter. "It can't scan the entire device."

—Larry Greenemeier

BY THE NUMBERS

Number of annual fatalities from car accidents—the top mechanism of injury death in the U.S.—per 100,000 people in rural areas. The rate in urban areas is much smaller: only 11 automobile fatalities per 100,000 people.

28

COURTESY OF TAL SHOMRAT AND MICHAEL LEVIN *(top)*; SOURCE: "SAFETY IN NUMBERS: ARE MAJOR CITIES THE SAFEST PLACE IN THE UNITED STATES?" BY SAGE R. MYERS ET AL., IN *ANNALS OF EMERGENCY MEDICINE*. PUBLISHED ONLINE JULY 25, 2013 *(bottom)*

Maryn McKenna is a journalist, a blogger and author of two books about public health. She writes about infectious diseases, global health and food policy.

The Pertussis Parable

Doctors race to protect kids as whooping cough vaccines wear off

By late summer 2010 an alarming number of children in California had developed pertussis, or whooping cough—five times as many as in the first half of 2009. David Witt, a physician and infectious disease specialist who works at Kaiser Permanente San Rafael Medical Center, cared for some of those sick children. His practice lies in the heart of Marin County, the famously counterculture spit of land north of San Francisco. At first, he assumed that the outbreak was a consequence of parents refusing vaccinations for their children. As the incidence continued to climb month after month, however—not just in northern California but all across the state—Witt began to wonder whether something else was going on.

Working with his college-age son Maxwell and his pediatrician colleague Paul Katz, Witt retrieved the records for 132 Kaiser Permanente patients younger than 18 who had tested positive for pertussis between March and October 2010.

"The bulk of the cases were in fully vaccinated children between eight and 12 years old," Witt says. "That was a total surprise."

As Witt's small study spotted, and larger ones have since confirmed, protection granted by the vaccine, which has been used for the past two decades, is wearing off much faster than public health planners anticipated. Rates of pertussis increased at least threefold between 2011 and 2012 in 21 states. Whereas some of these cases occurred among children who had never been vaccinated, most of the affected children had in fact received vaccines; those inoculations simply failed to safeguard them over the long term.

Now health authorities are scrambling to devise new strategies for protecting kids. There are no easy solutions. No one is developing a better vaccine to replace the current one. Attempting to recommend additional shots would trigger years of public health debate, and it is not clear whether extra doses of vaccine would make a difference. Even discussing the problem provokes uneasiness: with antivaccine sentiments and vaccine refusal at historic highs, nobody wants to impeach one of public health's crucial tools.

ADVERSE REACTIONS

BEFORE A VACCINE BECAME AVAILABLE in the 1940s, many parents learned firsthand that pertussis was a terrible disease. The bacterium that causes it, *Bordetella pertussis,* produces a toxin that damages the tiny sweeping hairs that coat the lining of the lungs, preventing them from clearing the airways of mucus and the microbial invaders. Following uncontrollable coughing fits—some of which are strong enough to cause seizures and brain damage—children wheeze and gasp for breath, giving the illness its name. In the pre-vaccine era, whooping cough afflicted as many as 200,000 children each year in the U.S. and killed about 8,000. The new vaccine shrank the incidence of pertussis from around 157 cases for every 100,000 members of the population to one in 100,000.

This success came at a cost, though. Researchers crafted the original pertussis vaccine from dead pertussis bacteria that could not reproduce but retained many microbial proteins by which immune cells could recognize and attack *B. pertussis* before it caused disease. Unfortunately, those whole-cell preparations also contained other molecular components that could cause unwanted immune system reactions, such as swelling near the injection site and, in rare cases, high fevers that could dangerously inflame the brain. "People didn't pay much attention to the reactions in the early days, because the death rate before the vaccine came along had been so staggering," says James Cherry, a longtime professor of pediatrics and vaccine researcher at the David Geffen School of Medicine at U.C.L.A.

Over the next few decades, however, concern surrounding the vaccine's side effects intensified. In the 1970s Sweden and Japan ceased using the vaccine altogether. A government study published in England in 1981 concluded that the vaccine caused permanent brain damage once in every 310,000 doses (a result

Illustration by Skip Sterling

that was later disputed). And in 1982 an NBC broadcast aired criticisms of the vaccine, turning public opinion against it and jump-starting the U.S. antivaccine movement.

The U.S. and other countries began industry-wide efforts to find a better vaccine, focusing on "acellular" formulas that used a few purified bacterial proteins to establish immunity rather than the whole cell, reducing the risk of inflammatory reactions. Researchers combined the new pertussis vaccine with vaccines against tetanus and diphtheria. DTaP, as it was known, was ready for the doctor's office in 1992. In the U.S., children receive it at two, four and six months; once between 15 and 18 months; and once between the ages of four and six, before they enter school.

From the start, public health authorities understood that an acellular vaccine might confer more temporary immunity than the problematic whole-cell vaccine. So, in 2005, they added a booster to the regimen to guarantee that children would be protected throughout adolescence. Officials determined the booster would be most effective for 11- to 12-year-olds but authorized it for use in any adult, eventually including pregnant women.

A FAILURE TO PROTECT

AFTER CALIFORNIA'S 2010 pertussis outbreak, additional outbreaks hit Wisconsin, Vermont and Washington, among other states, in 2012. Analyses of who was getting sick revealed the same pattern every time. Tom Clark, a physician and pertussis expert at the Centers for Disease Control and Prevention, describes it as a "striking stair-step appearance, rising by year: six, seven, eight, nine, 10 years old. If you go back several years [to when whole-cell vaccines were used], that stair-step is not there."

Most of the sick children had in fact received vaccines; those inoculations simply failed to safeguard them over the long term.

The stair-step indicated that the more time elapsed since a child's most recent pertussis shot, the more likely the child would develop whooping cough after exposure to the bacteria. Many of these children were too young to have received their booster, so researchers hoped that once children got their additional shots, the unpredicted vulnerability would cease. New data from the Washington State outbreak quashed that hope: 13- and 14-year-olds were catching pertussis even after they received their booster shot. Other studies demonstrated that the vaccine was behaving differently from the older, reactive one: children who had received even one dose of the older, whole-cell formula while it was still on the market were better protected against pertussis than those who received only the newer vaccine. (Of course, children who received the new vaccine were still better off than those who had never been vaccinated.)

Clark points out that the original research on acellular vaccine in the 1980s tested whether it would protect but not for how long it would protect. Some diseases for which acellular vaccines are typically used, such as Hib meningitis, are only dangerous to children for a short time early in life, so long-lasting immunity is not necessary. Today, however, immunologists have better laboratory tools and a much more nuanced understanding of how immunity is evoked and sustained. "A lot of what you would do to develop a vaccine today was never done for the pertussis vaccine," Clark says.

"The big answer is that we need a better vaccine," says Mark Sawyer, a professor of clinical pediatrics at the University of California, San Diego, and chair of a working group collaborating with the Advisory Committee on Immunization Practices (ACIP), which helps to set federal vaccine policy. "But the ACIP can't just make that happen. That is up to the scientists who would do a study of what would make a better vaccine, and it is up to the pharmaceutical companies."

If a new vaccine were formulated, demonstrating its superiority would be challenging. Every developed country vaccinates its children against pertussis, so there is no large unprotected population that could help prove a new vaccine's worth. And before encouraging manufacturers to consider developing a new vaccine, federal planners would have to weigh the unintended consequences of the endeavor. Diverting too much of the manufacturers' limited resources to one new vaccine could cause shortages of others, for example. Another concern is whether parents would heed the advice to bring children in for yet more shots.

The ACIP has been researching the problem for more than a year. The committee is in uncharted territory because this type of failure has never occurred with any other vaccine. In June the working group concluded that because the booster's protection against pertussis is so short-lived, adding more shots to the typical regimen would do little to reduce the overall prevalence of pertussis. The group therefore advised the committee not to change policy to include a second booster in adulthood but rather to increase the number of pregnant women who get their booster in the first place. The CDC estimates that currently only 6 percent of pregnant women receive the shot. Yet newborns, who cannot be vaccinated, are the most vulnerable to the dangerous effects of pertussis; improving the immunity of their closest contacts could be the best way to prevent pertussis deaths.

Given the current vaccine's faults, Clark says bluntly that in the general population "there's going to be a lot of pertussis." But he adds that although pertussis cases are increasing, deaths are not; when vaccinated children develop whooping cough, they have milder symptoms. So the newer pertussis vaccines are still valuable because they reduce not just the likelihood of death and severe illness but also the health care spending—not to mention emotional trauma—that accompany those dire results. On that basis, Sawyer says, public health officials should urge the 90 percent of American teens and adults who failed to get their booster shot to receive one and thereby protect both themselves and the most vulnerable among us. "We do need a new vaccine," he says. "But we can do a lot better with the ones we have." SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/oct2013

David Pogue is the personal-technology columnist for the *New York Times* and host of NOVA's *Making Stuff* on PBS this fall.

Edit Your Photos? Feed the Meter

If you want certain software, you're going to have to pay up—month after month after month

You can't please all the people all the time, and nobody knows it better than tech companies. Any little change will infuriate some subset of your customers: change the layout, change how a feature works, change the system requirements. Even if the overall outcome is a step forward, a bit of customer disgruntlement is just a cost of doing business.

Apparently, however, it's also possible to enrage just about your entire customer base at once. That's what Adobe managed to do this spring when it announced that it would no longer *sell* Photoshop, Illustrator, InDesign and its other professional design programs. Instead this software is now available only for rent, for a perpetual monthly or yearly fee.

This idea—software as a subscription—is catching on. Earlier this year Microsoft began offering its Office suite (Word, Excel, PowerPoint) for a $100-a-year subscription, although you can still buy the programs the old way if you prefer. Big-corporation software, supplied by companies such as IBM and Oracle, has been subscription-only for years.

So what's behind the Photoshopper fury?

Adobe points out that the annual big-upgrade cycle—a relic of the olden days, when software had to be shipped on floppies or CDs—no longer benefits anyone. The rental program is supposed to offer steady incremental improvements all year long. Wouldn't you rather have new features available as they are written, rather than waiting for next year's new version? That's worth something, right?

But what about the money? Adobe software will cost more—sometimes. In bygone days, you could buy Photoshop for $600. Each year's upgrade cost $200, but you could skip upgrading for a while, and the old software would continue to work just fine. If you upgraded only once in five years, you'd have spent $800, compared with $1,200 for renting.

On the other hand, subscribing is a better deal for dabblers, those who can now rent Photoshop for $30 a month, starting and stopping as needed. And hard-core professionals who use all the Adobe Creative Suite programs come out way ahead with the rental program. They pay $50 a month for all of them.

So it's not necessarily the pricing that's stirring up emotions. No, the greater factor is something nobody's talking about: the shift from owning to renting.

There's nothing inherently wrong with monthly fees. We don't bat an eye when we write checks for cable TV, Internet, phone, gas, electric, magazines, mortgage, and so on. We don't even object to paying monthly fees for digital services. Netflix, after all, has some 36 million people cheerfully paying monthly. What's the difference?

Here's the answer: visible deliverables.

We're happy to pay monthly when we can see what we're getting for it: TV shows or movies or heating or cooling or articles.

But paying a monthly fee for software doesn't feel the same. We download a program, and there it sits. Month after month we pay to use it, but we get nothing additional in return.

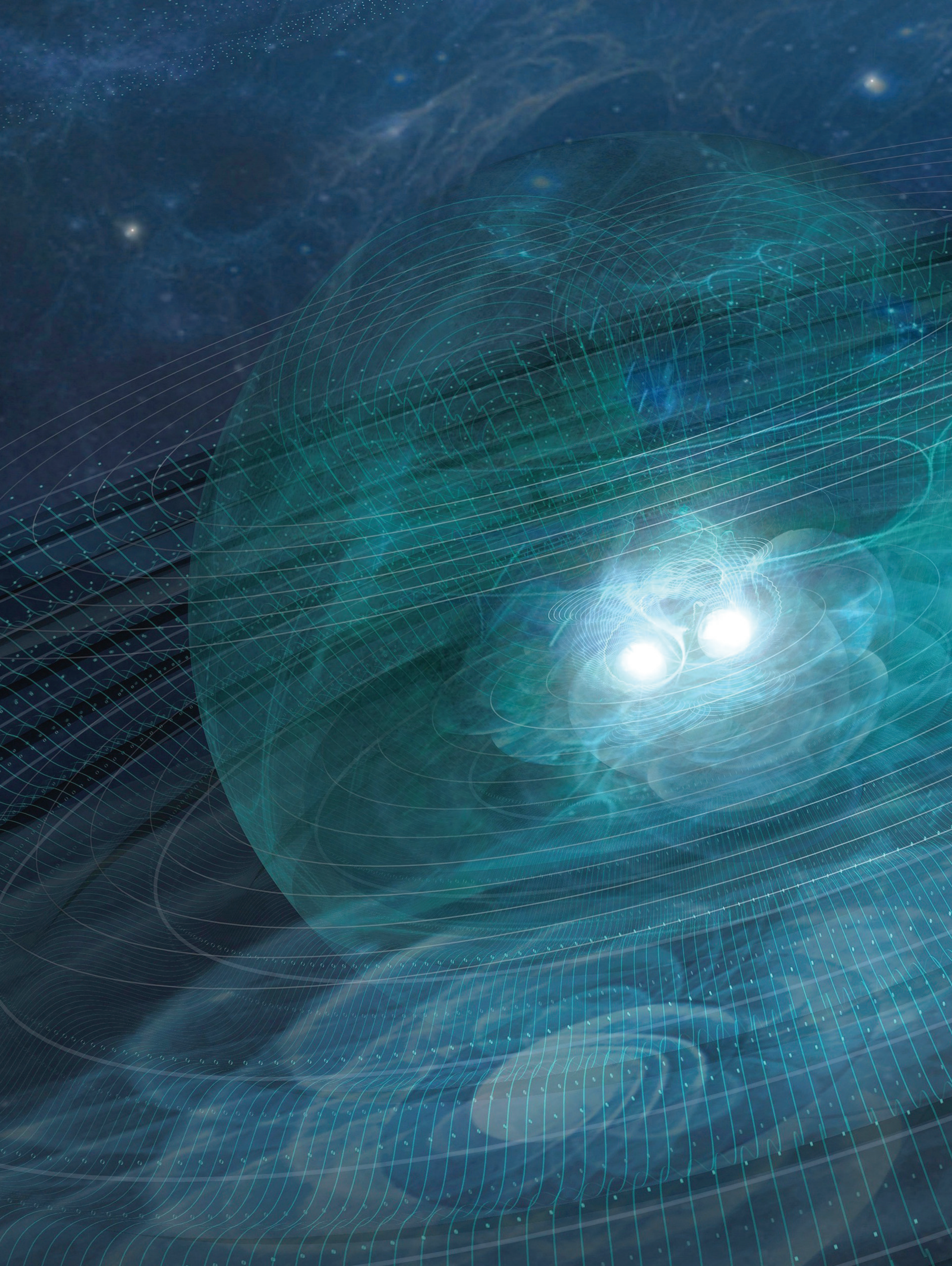
That's why the Adobe model isn't the same thing as those corporate programs from IBM and Oracle. They come with a fleet of consultants and trainers. You can see the service you're paying for.

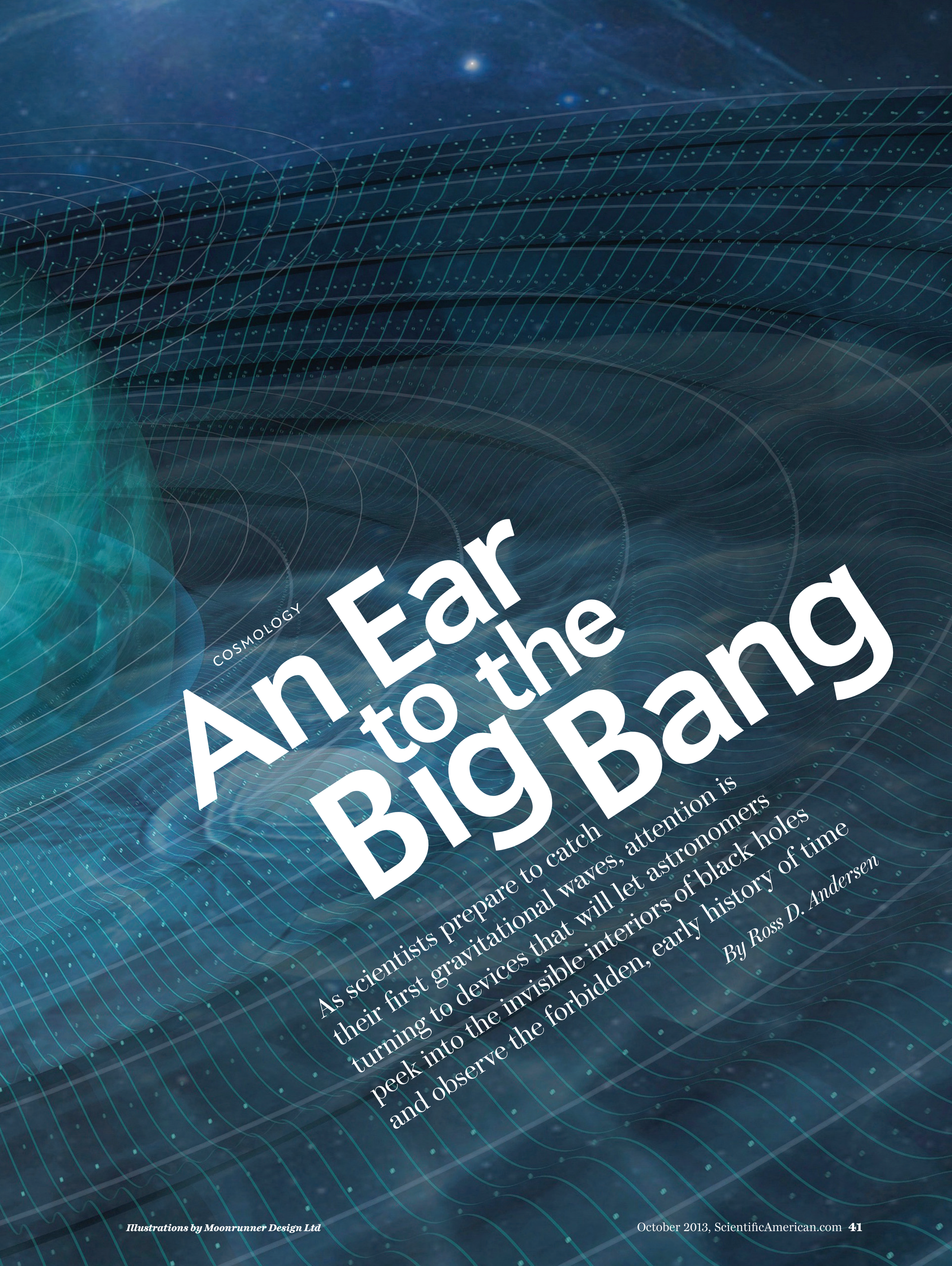
Maybe Adobe plans to improve its programs so often, so steadily, that we'll come to view them as a service worth paying continuously for. But for now, they're asking us to pay for a single, unchanging hunk of code as though it's a continuously delivered amenity like cable TV or cell-phone service. We sense the breakdown of the tacitly understood model—we feel like we're paying something for nothing.

No wonder we're upset, both intellectually and emotionally. Adobe has the market share to do what it wants. But that doesn't mean it can't alienate all its users. We can only hope other companies will watch and learn. And keep their wares buyable. SA

SCIENTIFIC AMERICAN ONLINE
Six questions about software subscriptions: ScientificAmerican.com/oct2013/pogue

Illustration by Richard Mia





COSMOLOGY

An Ear to the Big Bang

As scientists prepare to catch their first gravitational waves, attention is turning to devices that will let astronomers peek into the invisible interiors of black holes and observe the forbidden, early history of time

By Ross D. Andersen

Illustrations by Moonrunner Design Ltd

Suppose you want to glimpse the beginning of time, the very first moments of cosmic creation.

You might start by building a perfect telescope, an instrument so powerful that it could see to the far end of the observable universe. You'd scout out a dry mountaintop, far from the star-fading glow of civilization. You'd level out a perch near its peak and place a state-of-the-art observatory atop it. You'd outfit it with a gigantic mirror—something much larger than could be launched into space—and equip it with a series of sophisticated detectors. You'd spend several years and several billion dollars, so that every last photon was within your reach. But what could you see with it? Say it was that one night in an astronomer's thousand, when the moon hides below the horizon, and the sky appears as a clear, dark dome overhead. What jewels would glitter out from that purplish-black showcase of celestial sights?

Quite a few, it turns out. In the foreground, you would see a smattering of planets, their orbits adrift against the fixed whirl of the constellations. Beyond them, local stars would loom large against a backdrop of fainter specks of white. In the sky's darker corners, galaxies would glow, some from hundreds of millions of light-years away. If you pointed your perfect telescope at exactly the right spot, it could reveal deeper cosmic recesses still. It could take you to the very first stars—the huge hydrogen and helium spheres, whose fiery surfaces illuminated the young universe.

But light has limits; it can't show you the *entire* universe. You could look through a telescope all night, every night, and never see into the center of a black hole or back to the dawn of time itself. For the first few hundred thousand years after the big bang, photons of the infant universe stayed trapped in a dense soup of light-suffocating particles, like fireflies sealed into sludge. It was not until 380,000 years after the big bang that the universe cooled into something transparent and, for our purposes, legible—a void through which the flash of creation could be seen. We call this flash the cosmic microwave background (CMB), and

IN BRIEF

Astronomers stand at the cusp of a new era. Soon they will be able to observe the universe not just with light waves but with gravitational waves as well.

Gravitational waves offer a view into the universe that has heretofore been hidden. They can reveal what lies inside a black hole's event horizon and offer a glimpse of the earliest moments of the universe.

Earth-bound gravitational-wave observatories should make their first discoveries in the next few years. Beyond that, a scuffle is brewing over two different technologies that might go into a space-based gravitational-wave observatory.

it is the dominant text of modern cosmology. It is also a wall, a barrier in time, beyond which darkness reigns.

For centuries now the careful collection of ancient light has been the dominant way to observe the universe, the key to cosmology's most ambitious experiments. But light cannot illuminate the beginning of time, no matter how large and sophisticated our telescopes grow. To see beyond the CMB, back toward the dawn of the universe, cosmologists must turn to gravity, a force that leaves echoes of its own strewn across space—echoes we call gravitational waves. To detect these echoes, we will need a new kind of instrument, something very different from a telescope.

THE FIRST DETECTORS

The quest to build an instrument that can detect gravitational waves began decades ago, but so far it has proved fruitless. As of this writing, LIGO, the $570-million Laser Interferometry Gravitational Wave Observatory, represents the best such attempt [see "Ripples in Spacetime," by W. Wayt Gibbs; Scientific American, April 2002]. It consists of three instruments, two in Washington State and one in Louisiana. Each of these is an engineering marvel, a laser-based measuring stick capable of detecting a twitch the width of an atom. LIGO works by shooting laser beams down two perpendicular arms and measuring the difference in length between them—a strategy known as laser interferometry [*see bottom right box on page 45*]. If a sufficiently large gravitational wave comes by, it will change the relative length of the arms, pushing and pulling them back and forth. In essence, LIGO is a celestial earpiece, a giant microphone that listens for the faint symphony of the hidden cosmos.

Like many exotic physical phenomena, gravitational waves originated as theoretical concepts, the products of equations, not sensory experience. Albert Einstein was the first to realize that his general theory of relativity predicted the existence of gravitational waves. He understood that some objects are so massive and so fast moving that they wrench the fabric of spacetime itself, sending tiny swells across it.

How tiny? So tiny that Einstein thought they would never be observed. But in 1974 two astronomers, Russell Hulse and Joseph Taylor, inferred their existence with an ingenious experiment, a close study of an astronomical object called a binary pulsar [see "Gravitational Waves from an Orbiting Pulsar," by J. M. Weisberg et al.; Scientific American, October 1981]. Pulsars are the spinning, flashing cores of long-exploded stars. They spin and flash with astonishing regularity, a quality that endears them to astronomers, who use them as cosmic clocks. In a binary pulsar system, a pulsar and another object (in this case, an ultradense neutron star) orbit each other. Hulse and Taylor realized that if Einstein had relativity right, the spiraling pair would produce gravitational waves that would drain orbital energy from the system, tightening the orbit and speeding it up. The two astronomers plotted out the pulsar's probable path and then watched it for years to see if the tightening orbit showed up in the data. The tightening not only showed up, it matched Hulse and Taylor's predictions perfectly, falling so cleanly on the graph and vindicating Einstein so utterly that in 1993 the two were awarded the Nobel Prize in Physics.

The trouble for LIGO is that it can hear these binary pulsars only in their final moments, when their starry spiral accelerates, churning out a series of strong waves that propagate across space like an invisible cosmic death rattle. Our universe may be large and star-filled, but binary collapses are rare. To hear them with any regularity, you have to train your ear on a gigantic chunk of the cosmos. Until recently, LIGO's reach was limited to a region of space that can go centuries without a binary collapsing within its borders.

But LIGO's first build was a dry run, a way of working out the engineering kinks that accompany instrument integration on a kilometers-wide scale. Now that LIGO's engineers know they can make a complex detector work, they are upgrading its sensitivity, so that soon it will be able to detect a binary collapse from 500 million light-years away—an improvement that could allow it to hear hundreds of these events a year. Indeed, most astrophysicists expect LIGO to achieve the first direct detection of gravitational waves within months of its return in 2016—the 100th anniversary of Einstein's prediction.

ATOM WAVES

Despite its considerable cost, LIGO's ambitions are limited. In some ways, it is a proof-of-concept mission, a necessary first step before gravitational-wave science ascends to its most natural environment: space. Our planet is a terrible place for a gravitational-wave observatory because its crust is constantly awash in seismic noise—the product of booming tectonic collisions underneath Earth's surface and sloshing oceans atop it. All of this shaking and quaking can easily drown out the thin, matter-shifting wisp of a gravitational wave. To hear a wider variety of them, we need a detector in the abyss beyond the atmosphere, where conditions are considerably more serene.

At the NASA Goddard Space Flight Center, two teams of engineers are positioning themselves to be the first to put a gravitational-wave detector in space. The older of these teams has been refining its mission, the Laser Interferometer Space Antenna (LISA), for decades. The LISA mission is an audacious engineering project, demanding a level of precision that makes LIGO look Lego-like by comparison. It requires the launch of three spacecraft that orbit the sun in the form of an equilateral triangle with sides five million kilometers long. Once the spacecraft are in place, the distance between them will be measured, continually, with lasers. If a gravitational wave rolls through, disturbing the spacecraft and distorting the triangle, the lasers will capture it.

LISA's basic design has not changed much since a few pioneers of gravitational-wave science sketched it onto a cocktail napkin at a NASA physics conference more than three decades ago. But it has grown refined over time, as engineers have grappled with the practical challenge of bringing its ambitious design to life. In the late 1990s and early 2000s, LISA emerged as an early contender to become NASA's next flagship astrophysics mission, following the James Webb Space Telescope (JWST). But in the years since, the JWST has swallowed most of NASA's astrophysics budget, and with no detections at LIGO, astronomers

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have found it hard to make a case for a multibillion-dollar gravitational-wave detector. A green light for a mission such as LISA could be more than a decade away.

These delays have created space on NASA's drawing board for novel ideas about how to detect gravitational waves in space. A small team within the agency's Advanced Concepts division recently began developing a new kind of gravitational sensor, based on a nascent technology called atom interferometry. The team is loosely organized, and so far its work can hardly be said to constitute a full-blown mission. Its principal leaders—Babak Saif, an interferometer engineer for the JWST, and Mark Kasevich, a professor of applied physics at Stanford University, are both engrossed in other pursuits. This is a side project for them, something to tinker with and dream about in the margins of their workweek.

In February, I visited Saif at one of Goddard's laser labs, where he is slowly starting to build an atom interferometer, a technology that he expects to form the basis of a smaller, more nimble gravitational-wave detector. As one of the world's most prestigious space research labs, Goddard is home to a slew of scientists with gaudy academic pedigrees, but Saif had humbler beginnings. After immigrating to the U.S. from Iran at the age of 17, Saif's family settled in northern Virginia, where he began taking classes in science and mathematics at a local community college. Saif worked nights at a gas station to support himself and proved himself a quick study at school. In 1981 he transferred to the Catholic University of America on a full scholarship, and in the years since he has completed two Ph.D.s. Before coming to Goddard, Saif spent a decade at the Space Telescope Science Institute, where he designed the interferometer that will eventually test the mirrors of the JWST. Saif's interferometer will ensure that the mirrors are accurate to the nanometer scale to avoid a repeat of the fiasco that befell the Hubble Space Telescope when it reached orbit with a misaligned mirror.

Saif explained that his and Kasevich's mission concept is similar to LISA's in that it involves measuring the distance between orbiting spacecraft. But whereas LISA measures changes in distance by combining light from the laser beams shot between the spacecraft, Saif and Kasevich's mission will instead employ atoms sitting just outside the spacecraft [*see top right box on opposite page*]. Because the atom interferometer measures distances between atom clouds, not spacecraft, it can be much smaller. Its current design calls for arm lengths that are 5,000 times shorter than the LISA design.

The power of this technique is in its precision. A gravitational wave might shift the distance between the spacecraft by less than a trillionth of a millimeter, and yet the atom interferometer will detect the difference.

Not everyone is enthused about atom interferometry, however. The limited funding that exists for space science has led to tension between Saif's atom interferometry team and the LISA team. The two mission concepts are similar in some ways. Both require precision coordination between spacecraft, and both make use of interferometry to make precise measurements. But according to Saif, the switch from light interferometry to atom interferometry will allow for a cheaper and more sensitive detector and a reduction in the enormous distance between spacecraft; the latter has long been a sticking point for LISA's critics.

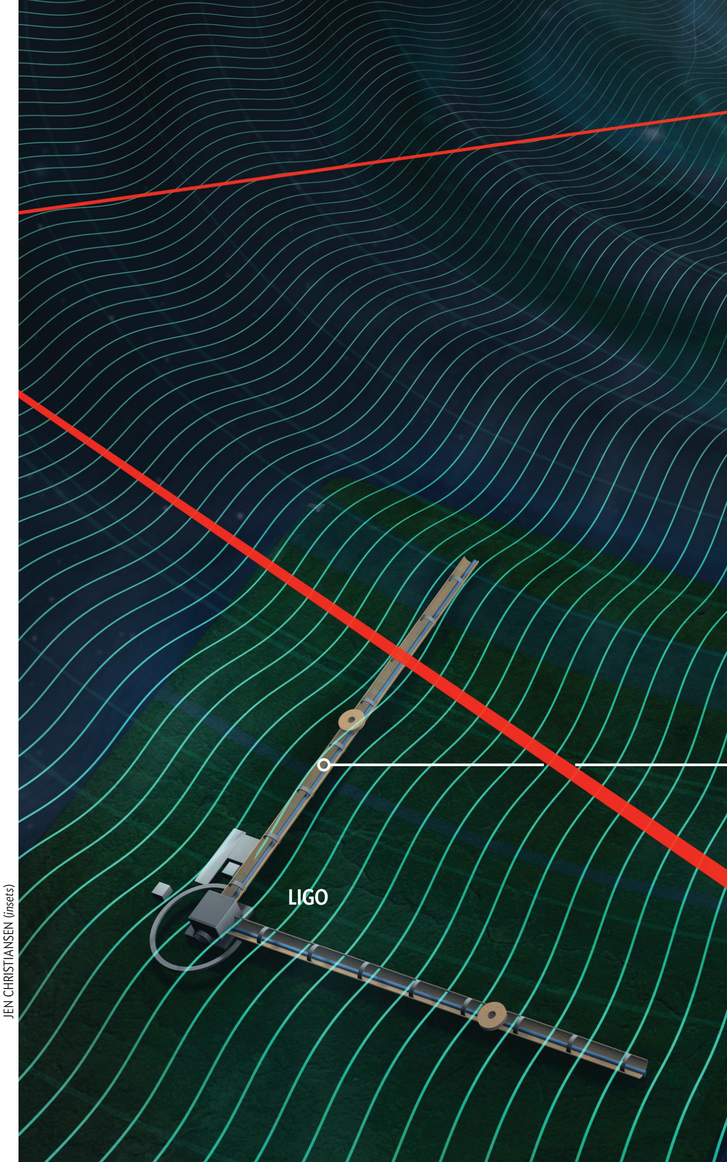
The LISA folks fire back by attributing the cost savings of atom

HOW IT WORKS

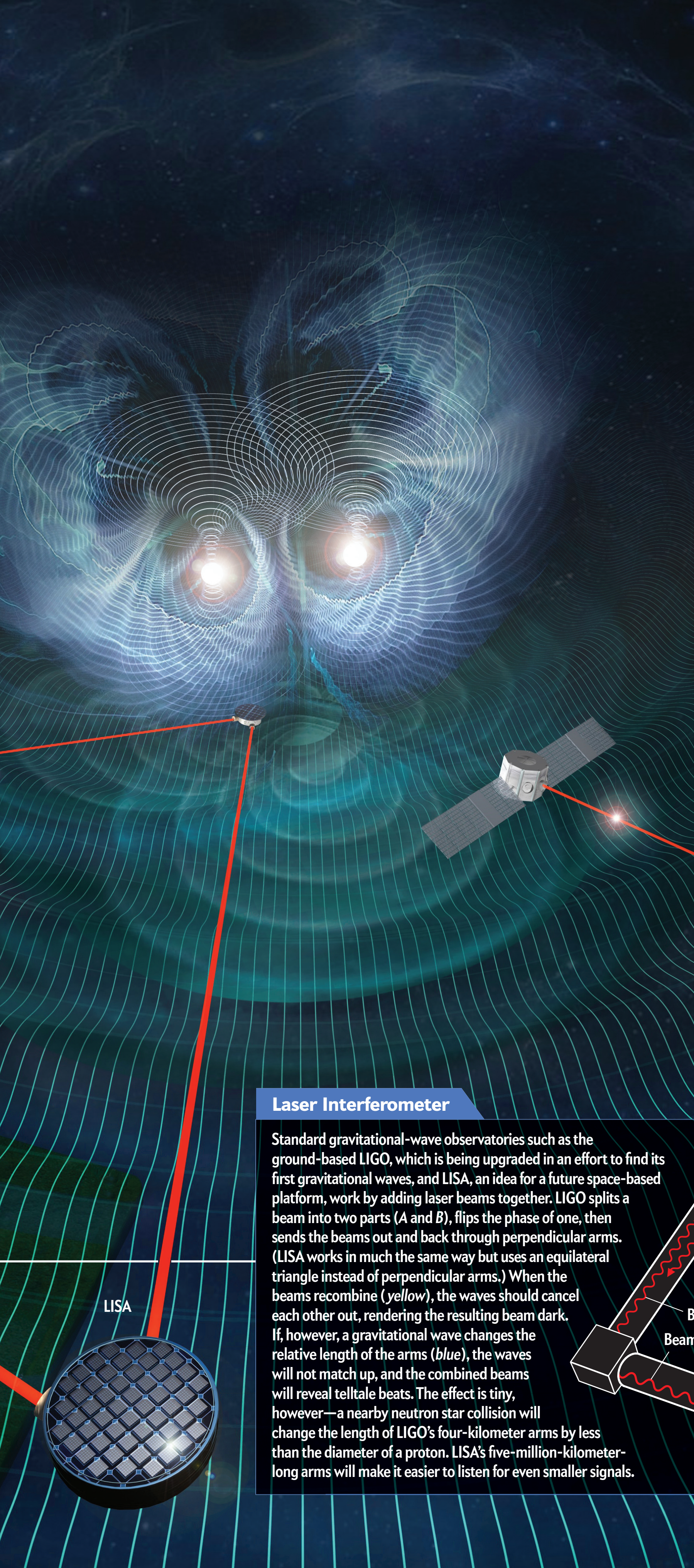
The Universe According to Gravitational Waves

Albert Einstein taught us that matter and energy can bend the very fabric of spacetime. Move enough mass, and the motion will create spacetime ripples that undulate across the universe. Such gravitational waves are the only way we can observe events that cannot be seen using light—the crash of two black holes, for example, or the tumult of quantum fluctuations in the nanoseconds after the big bang.

Big bang echoes will be exceptionally difficult to detect, however; only a space-based observatory would be up to the task. The two concepts on this page are the drawing-board versions of a future mission that would have the power to hear the universe's first echoes.

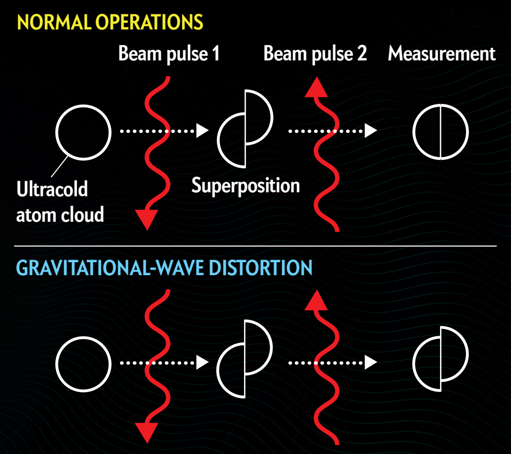


JEN CHRISTIANSEN (*insets*)



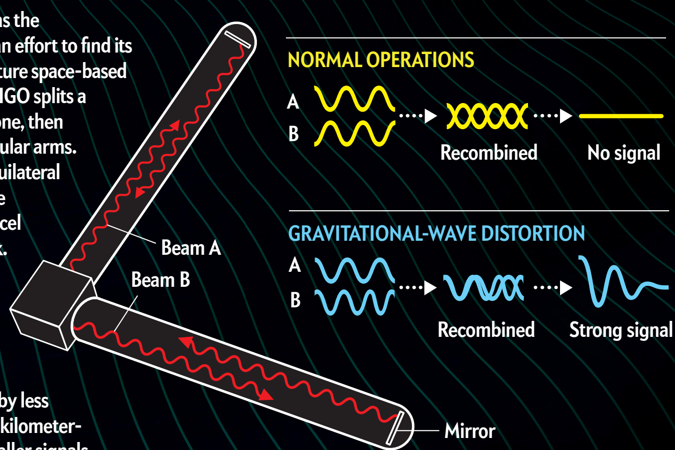
Atom Interferometer

A new approach to measuring gravitational waves would use clouds of ultracold atoms that sit just outside of two spacecraft 1,000 kilometers apart. First, laser beams put each cloud into a superposition of two parts, with two different velocities. After 10 seconds, another laser reverses the process, so that the two parts start coming back together. As the atom clouds overlap again, more lasers measure them. If during the 20 seconds it takes for the process to run its course a gravitational wave rolls through the space between the spacecraft, it will shift the distance between the cloud pairs by a tiny amount, imparting a measurable change in the final state of the atoms.



Laser Interferometer

Standard gravitational-wave observatories such as the ground-based LIGO, which is being upgraded in an effort to find its first gravitational waves, and LISA, an idea for a future space-based platform, work by adding laser beams together. LIGO splits a beam into two parts (*A* and *B*), flips the phase of one, then sends the beams out and back through perpendicular arms. (LISA works in much the same way but uses an equilateral triangle instead of perpendicular arms.) When the beams recombine (*yellow*), the waves should cancel each other out, rendering the resulting beam dark. If, however, a gravitational wave changes the relative length of the arms (*blue*), the waves will not match up, and the combined beams will reveal telltale beats. The effect is tiny, however—a nearby neutron star collision will change the length of LIGO's four-kilometer arms by less than the diameter of a proton. LISA's five-million-kilometer-long arms will make it easier to listen for even smaller signals.



interferometry to its newness. They point out that wide-eyed boosters of new technologies often underestimate the heavy costs of development. A design's real price tag emerges only once a mission is in place, they say, because only then do you begin to see the more difficult engineering challenges that come with system integration.

THE TROUBLE WITH LIGHT

AT GODDARD, I ASKED SAIF what motivated him to spend his spare time on such a speculative mission, one that may never fly. He told me it was the possibility of new physics that fascinated him. He said he expects the next few decades to usher in an epochal transition in the field of astronomy—a switch from the photon to the graviton.

Indeed, gravitational waves help to make up for a host of light's scientific liabilities—and not just its inability to tell us about the beginning of time. Light has other limitations as an information carrier. To start with, it is the product of interactions between particles. When light springs out into the universe, it announces the occurrence of tiny events, such as the fusing of hydrogen into helium inside of stars. It is a record of the infinitesimal. If we want to learn how large objects move through spacetime, we have to aggregate light from scores of these tiny events and use it to make inferences. We have to piece together a surface-layer mosaic.

Worse still, light biases our view of the cosmos because it tends to come from thermodynamically intense environments. Astronomy's large, signalworthy splashes of light are the products of fiery events, such as stars in their supernova death throes. When we summon the universe to mind, the structure we see is slanted toward hot, chaotic places.

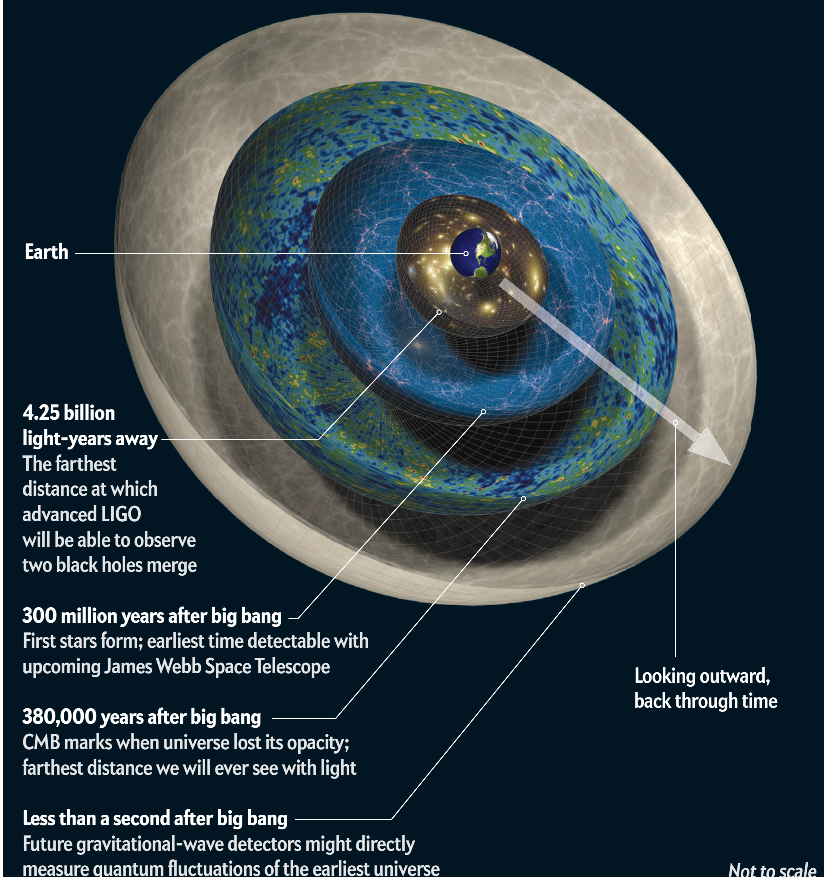
Light signals are fragile, too. They often dilute or disappear altogether, as they make their way across the cosmos. Some are absorbed by giant gas clouds in their path. Others scatter or fall into deep gravity wells, never to be heard from again. The deepest of these wells are supermassive black holes, the pillars of cosmic structure around which entire galaxies pivot. Scientists want to know more about these black holes—especially what happens when two of them merge together—but no light from a black hole ever reaches our telescopes or eyes because photons, speedy as they are, cannot escape the suction of a black hole's center.

Instead cosmologists have to content themselves with light that a black hole does not devour, light that springs out from its periphery, from matter caught in the furious distortions of spacetime around it. Luckily, gravitational-wave signals aren't nearly as impressionable as light. They don't scatter or dilute. Instead they ripple through the universe cleanly, impervious to the astrophysical giants in their path.

COSMIC HORIZONS

What We Hope to See (Beyond)

Gravitational waves pass through boundaries that light cannot. They can transport information about what happens inside the event horizons of black holes, and they can pass through the cosmic microwave background (CMB) radiation, the barrier of light that will always prevent us from seeing the universe before it turned 380,000 years old. They will give us ears into every corner of the cosmos.



PRIMORDIAL ECHOES

A FEW WEEKS AFTER MY TRIP to Goddard, I visited David Spergel, chair of Princeton University's astrophysics department and one of the world's preeminent cosmologists. Spergel chairs the National Research Council's decadal survey committee on cosmology and fundamental physics, the reports of which play a large role in determining the long-term research priorities for cosmology. NASA is known to pay especially close attention to its recommendations, which means Spergel has an outsized say in what science missions the agency decides to fly.

As we sat down in his office, Spergel began detailing the advantages of gravitational waves. Unlike light, he explained, the universe has always been transparent to gravitational waves.

> **"If we fly one of these spacecraft and don't hear huge black holes colliding, something is very wrong with our picture of the universe."**

There was no primordial era during which they were hidden by strange cosmic conditions. Indeed, gravitational waves would have no trouble rippling out to us from the very first moments after the big bang. But how do we know any were around then?

"To produce gravitational waves, you have to move a lot of matter around very quickly, and one way you could do that is with a phase transition," Spergel told me. A phase transition occurs when a physical system changes states. The classic example is water freezing into ice, but there are also cosmic-size phase transitions, some of which occurred shortly after the big bang. Take quarks, for example. Today quarks are mostly bound up in the nuclei of atoms, but in the first microseconds of the universe, they buzzed around freely in what cosmologists call a quark-gluon plasma. At some point, the universe transitioned from this quark-gluon plasma to a new phase populated by protons and neutrons.

"If you had a first-order phase transition like that, bubbles would form within the plasma, causing a whole lot of matter to move around quite violently," Spergel said. First-order phase transitions occur suddenly, when bubbles of a new phase form in the midst of the old one. These bubbles expand and collide until the old phase disappears completely, completing the transition. The chaos of this process would have generated strong sets of gravitational waves, which may be washing over us today. Their detection could offer our first glimpse into the universe's infancy.

And there might be older gravitational waves, still. In some inflationary models of the universe, the first burst of exponential cosmic expansion coincides with quantum fluctuations of space-time—ripples that cause certain regions of the universe to expand faster than others. These fluctuations could have given rise to a special species of gravitational waves, called stochastic gravitational waves, that would have formed when the universe was less than a trillionth of a trillionth of a trillionth of a second old [see "Echoes from the Big Bang," by Robert R. Caldwell and Marc Kamionkowski; Scientific American, January 2001].

"Most inflationary models of the universe predict this stochastic gravitational-wave background coming from the very early parts of the universe," Spergel told me. "If we could observe it, it could show us fundamental physics. It could show us what the universe looked like at energy scales that are 10^{13} times what we're getting at the Large Hadron Collider," he said.

Going after stochastic gravitational waves is high-stakes science. Detecting them would be very difficult. It would require an especially sensitive instrument, and painstaking data analysis, to sift out the precious primordial waves from the legions of gravitational-wave signals that would bombard a space-based detector. If you could collect this signal from every corner of the heavens and scrub it of stray noise, you would have a stochastic gravitational-wave background, an all-sky map of gravitational waves. You'd have a new foundational text of cosmology to pore over.

The mission designs for both LISA's and Saif's atom interferometry concepts are aimed at detecting gravitational waves from more conservative targets, such as black hole mergers. In headier days, LISA's designers dreamed up a Big Bang Observatory, a successor mission tuned specifically to stochastic gravitational waves. But such an observatory was always a long shot, an idea that was decades away from implementation. Saif told me he would like to reverse the mission order and go after stochastic gravitational waves first, but so far the designs he has worked up target the same signals as LISA. The conservative approach is a diplomatic sop to the wider community of astrophysicists, who are intrigued by gravitational-wave science but want it to start slow, by targeting objects already known to exist.

"Supermassive black hole collisions are the bread-and-butter work of gravity-wave experiments," Spergel told me. "If we fly one of these spacecraft and we don't hear huge black holes colliding, then something is very wrong with our picture of the universe," he said. "But the home-run signal is the cosmology."

At some point, Spergel's decadal survey committee may find itself choosing between black holes and cosmology and, perhaps, atom interferometry and light interferometry. The committee is set to reconvene midway through the decade to evaluate and adjust the course it set in 2010. By the time the next such survey comes around, the JWST will have launched, presumably freeing up money for an ambitious space science mission.

As I stood to leave, I asked Spergel if he had an early favorite, if he thought Saif's mission would best LISA in the long haul. He told me that he isn't convinced the atom interferometry concept will win out, but he is convinced it's interesting enough to think hard about. Then he told me a story. "Many years ago, well before he won his Nobel Prize, I was talking to Steven Chu about how to do great science, and he told me something I've never forgotten," Spergel said, walking me out. "He said you have to put yourself in the position to do experiments that could be important," he continued. "I think both these experiments fall into that category." SA

MORE TO EXPLORE

Einstein's Unfinished Symphony: Listening to the Sounds of Space-Time. Marcia Bartusiak. Berkley Books, Penguin Putnam, 2000.

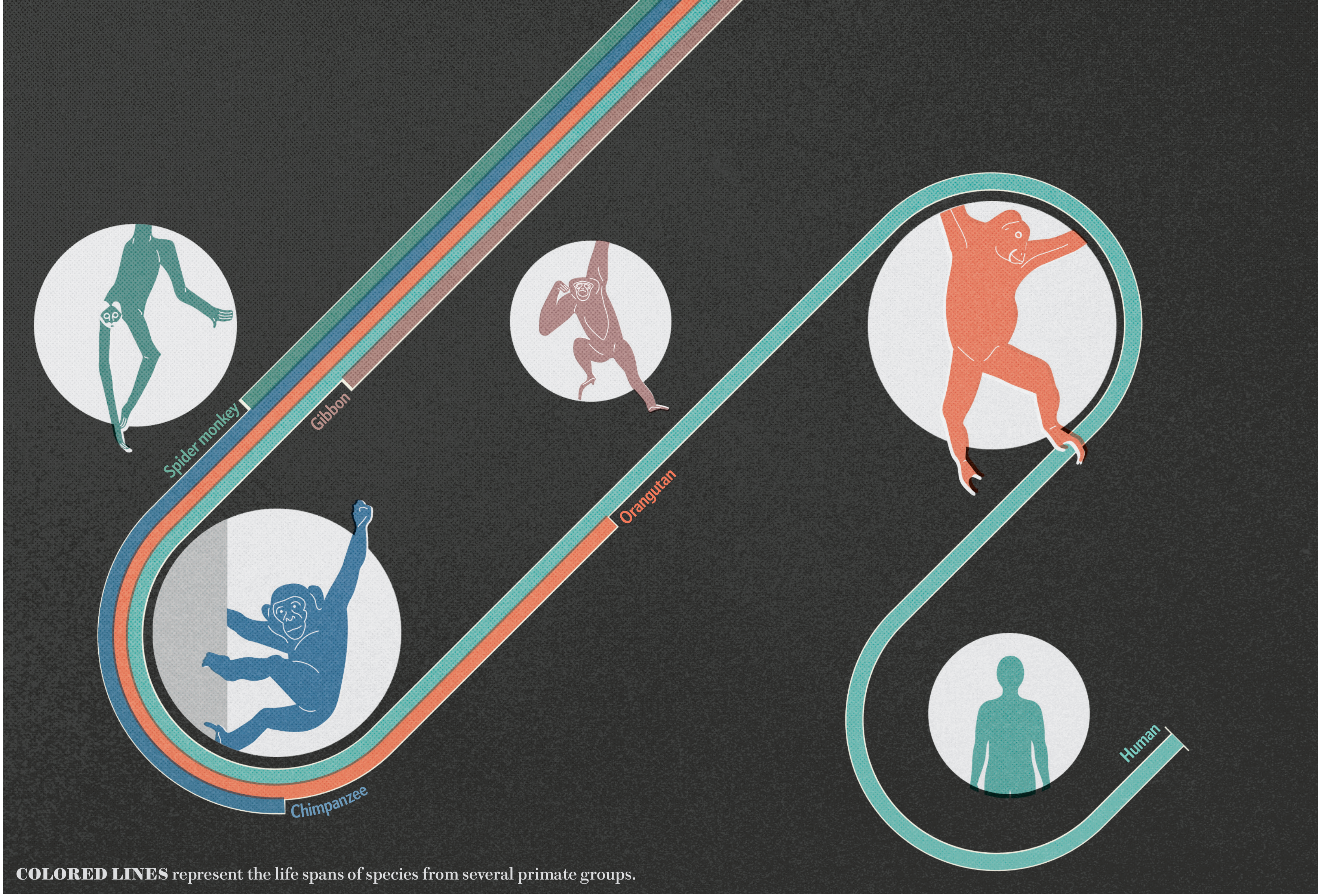
Gravitational Wave Detection with Atom Interferometry. Savas Dimopoulos et al. in *Physics Letters B,* Vol. 678, No. 1, pages 37–40; July 6, 2009.

LISA Project Office: **http://lisa.nasa.gov**

SCIENTIFIC AMERICAN ONLINE
See how atom interferometers detect gravitational waves in a video at **ScientificAmerican.com/oct2013/gravity**

EVOLUTION

Long Live the Humans



COLORED LINES represent the life spans of species from several primate groups.

Modern genomes and ancient mummies are yielding clues to why the life span of *Homo sapiens* far exceeds that of other primates

By Heather Pringle

Illustration by Gavin Potenza

Heather Pringle is a Canadian science writer and a contributing correspondent for *Science*.

On a Sunday morning in a decaying and dangerous inner-city barrio in Lima, Peru, an unmarked white van carrying nearly a dozen bodies rumbles to a stop on the grounds of the National Institute of Neurological Sciences. Seated in a small waiting area to the rear of the building, a throng of well-dressed researchers and government officials watches intently. As the driver clambers out, an assistant hustles off in search of a hospital gurney. Within minutes, two men wheel the first body into the institute's imaging unit.

Onlooker Caleb Finch, a biologist at the University of Southern California, has been waiting for this moment for months. Tall, gaunt and graying, with a Father Time–style beard, the 74-year-old scientist has devoted his career to the study of human aging. Our kind is remarkably long-lived compared with other primates. Our nearest surviving relatives, the chimpanzees, have a life expectancy at birth of about 13 years. In contrast, babies born in the U.S. in 2009 possessed a life expectancy at birth of 78.5 years. Finch has come to Lima to find out why—by peering into the distant past. The cadavers in the van belong to men, women and children who perished along this stretch of coastal desert as much as 1,800 years ago, long before the Spanish conquest. Cocooned in dusty textiles and interred in arid desert tombs, their naturally mummified bodies preserve critical new clues to the mystery of human longevity. As envoys from an era long before modern health care, they will offer case studies of aging in the past. Finch walks over to the van, grinning as he surveys the cargo. "That's a pack of mummies," he says.

Most researchers chalk up our supersized life span to the advent of vaccines, antibiotics and other medical advances, the development of efficient urban sanitation systems, and the availability of fresh, nutritious vegetables and fruit year-round. Indeed, much demographic evidence shows that these factors greatly extended human life over the past 200 years. But critical as they were to extending human life, they are only part of the longevity puzzle, Finch warrants. Marshaling data from fields as diverse as physical anthropology, primatology, genetics and medicine, he now proposes a controversial new hypothesis: that the trend toward slower aging and longer lives began much, much earlier, as our human ancestors evolved an increasingly powerful defense system to fight off the many pathogens and irritants in ancient environments. If Finch is right, future research on the complex links among infection, host defense and the chronic diseases of the elderly may revolutionize scientists' understanding of aging and how to cope with the challenges it brings.

AND MANY MORE

HINTS THAT MODERN HEALTH practices might not be solely responsible for our long life span have come from studies of contemporary hunter-gatherer groups. In 1985 Nicholas Blurton-Jones, a

IN BRIEF

Humans live far longer than other primates, a phenomenon that has traditionally been credited to modern medicine, food availability and sanitation systems.

But new research suggests that although these factors have extended human life span over the past 200 years, the trend actually began far earlier than that.

As human ancestors ate more meat, they evolved defenses against its attendant pathogens. These defenses contribute to longevity but foster disease later in life.

MEDICAL IMAGING **of ancient mummies such as Egyptian scribe Hatiay has revealed clogged arteries, suggesting that cardiovascular disease is not a modern affliction but rather the price humans pay for having a supercharged immune system.**

MICHAEL MIYAMOTO *AP Photo (mummy)*; COURTESY OF M. LINDA SUTHERLAND (*CT scan*)

biological anthropologist at the University of California, Los Angeles, set off by Land Rover across the trackless bush in Tanzania's Lake Eyasi basin. With field assistant Gudo Mahiya, Blurton-Jones traveled to the isolated camps of the Hadza, hunter-gatherers who lived much as their ancestors had, hunting baboons and wildebeest, digging starchy tubers and collecting honey during the rainy season from hives of the African honeybee. Journeying from one camp to another, the two researchers collected basic demographic data, checking each Hadza household and recording the names and ages of the inhabitants. Then the pair updated this census information six times in the 15 years that followed, noting down the names of all who had died and the causes of their death. In addition, Blurton-Jones obtained some earlier census data on the Hadza from two other researchers.

The Hadza lived—as ancient humans and chimpanzees did—in a natural environment teeming with pathogens and parasites. They lacked running water and sewage systems, defecating in a zone 20 to 40 meters away from their camps, and they rarely sought out medical care. Yet as Blurton-Jones and Mahiya discovered, the Hadza enjoyed much longer lives than chimpanzees did. Indeed, the Hadza had a life expectancy at birth of 32.7 years. And if they reached adulthood, they could expect to live 40 more years, nearly three times longer than a chimpanzee reaching adulthood. Some Hadza elders survived into their 80s. Clearly, their relatively long lives owed little to medical and technological advances.

Moreover, the Hadza were not alone. In 2007 two anthropologists, Michael Gurven of U.C. Santa Barbara and Hillard Kaplan of the University of New Mexico analyzed data from all five modern hunter-gatherer societies that researchers had studied demographically. Infections counted for 72 percent of the deaths, and each group revealed a very similar J-shaped mortality curve—with child mortality as high as 30 percent, low death rates in early adulthood and exponentially rising mortality after the age of 40. Then Gurven and Kaplan compared these curves with those of both wild and captive chimpanzees: the simians experienced the sharp uptick of adult mortality at least 10 years earlier than human hunter-gatherers. "It appears that chimpanzees age much faster than humans," concluded Gurven and Kaplan in their paper detailing the findings, "and die earlier, even in protected environments."

Yet when, exactly, did humans begin living longer? To obtain clues, anthropologists Rachel Caspari of Central Michigan University and Sang-Hee Lee of U.C. Riverside examined the re-

mains of 768 individuals from four ancestral human groups spanning millions of years. By assessing the degree of dental wear, which accumulates at a constant pace from chewing, they estimated the ratio of young adults around 15 years of age to older adults around age 30 (old enough to be a grandparent) in each of the four groups. Their studies revealed that living to 30 and beyond became common only recently in our prehistoric past. Among the australopithecines, which emerged in Africa around 4.4 million years ago, most individuals died before their 30th birthday. Moreover, the ratio of thirtysomethings to 15-year-olds was just 0.12. In contrast, *Homo sapiens* who roamed Europe between 44,000 and 10,000 years ago often lived to 30 or more, achieving a ratio of 2.08 [see "The Evolution of Grandparents," by Rachel Caspari; Scientific American, August 2011].

Calculating the life expectancy of early *H. sapiens* populations is challenging, however: detailed demographic data, such as that supplied by both census records and death registrations, are lacking for much of our long past. So Finch and his colleague Eileen Crimmins, a gerontologist at the University of Southern California, analyzed the earliest, virtually complete statistical set of that nature available—data first gathered in Sweden in 1751, decades before the advent of modern medicine and hygiene. The study revealed that mid-18th-century Swedes had a life expectancy at birth of 35. But those who survived bacterial infections and contagious diseases such as smallpox during childhood and reached the age of 20 could reasonably look forward to another 40 years.

To Finch, these findings raised a major question. The 18th-century Swedes lived cheek by jowl in large, permanent villages, towns and cities, where they were exposed to serious health risks unknown to small communities of mobile chimpanzees. So why did the Swedes live longer? The answer, it turns out, may lie in the meaty diets of their early human ancestors and the evolution of genes that protected them from the many hazards of carnivory.

Eighteenth-century Swedes lived cheek by jowl in large, permanent villages, towns and cities, where they were exposed to serious health risks unknown to small communities of mobile chimpanzees. So why did the Swedes live longer?

MEAT-EATING GENES

Chimpanzees spend most of their waking hours in a sweet pursuit: foraging for figs and other ripe fruits. In search of fructose-rich fare, they range over large territories, only occasionally using the same night nest twice in a row. They are skilled at hunting small mammals such as the red colobus monkey, but they do not deliberately set out searching for these prey. Nor do they consume large quantities of meat. Primatologists studying wild chimpanzees in Tanzania have calculated that meat makes up 5 percent or less of the simians' annual diet there, whereas research in Uganda shows that animal fat constitutes only 2.5 percent of their yearly fare by dry weight.

In all likelihood, Finch says, the earliest members of the human family consumed a similar plant-based diet. Yet sometime between 3.4 million and 2.5 million years ago, our ancestors incorporated a major new source of animal protein. As sites in Ethiopia show, they began butchering the remains of large, hoofed mammals such as antelopes with simple stone tools, smashing the bones to get at the fat-rich marrow, slicing off strips of meat, and leaving behind telltale cut marks on femurs and ribs. And by 1.8 million years ago, if not earlier, humans began actively hunting large game and bringing entire carcasses back to camp. The new abundance of calories and protein most likely helped to fuel brain growth but also increased exposure to infections. Finch suggests that this risk favored the rise and spread of adaptations that allowed our predecessors to survive attacks by pathogens and thus live longer.

The trend toward increasing carnivory would have exposed our ancestors to pathogens in several ways. Early humans who scavenged the carcasses of dead animals, and who dined on raw meat and viscera, boosted their chances of ingesting infectious pathogens. Moreover, as humans took up hunting large animals, they faced greater risks of lacerations and fractured bones when closing in on their prey: such injuries could lead to deadly infections. Even cookery, which may have emerged as early as one million years ago, if not earlier, posed perils. Inhaling wood smoke daily exposes humans to high levels of endotoxins and soot particles. Roasting and charring meat improves both the taste and digestibility but creates chemical modifications known as advanced glycation end products, which contribute to serious diseases such as diabetes. Our ancestors' later embrace of agriculture and animal husbandry, which began some 11,500 years ago, added new dangers. The daily proximity of humans to domesticated goats, sheep, pigs, cattle and chickens, for example, elevated the risk of contracting bacterial and viral infections from animals. Moreover, as families settled permanently in villages, sewage from humans and livestock contaminated local water supplies. Pathogenic bacteria thrived.

Even so, humans exposed to such health risks in 1751 in Sweden lived longer than their simian relatives. To tease out clues to this longevity, Finch began studying the scientific literature on chimpanzee and human genomes. Previously published studies by others showed that the two genomes were around 99 percent identical. But in the uniquely human 1 percent, evolutionary biologist Hernán Dopazo, then at the Prince Felipe Research Center in Valencia, Spain, and his colleagues discerned a disproportionately high number of genes that had undergone positive selection and that played key roles in host defense and immunity—specifically in a part of the defense system known as the inflammatory

response. Positive selection favors genes that hone our ability to survive and reproduce, which allows them to become more frequent in populations over time, a process that leaves a distinctive "signature" in the DNA sequence. Dopazo's findings added new weight to an idea growing in Finch's mind. He wondered if natural selection had endowed ancient humans with a souped-up system for fighting off the microbial threats and warding off other health hazards posed by increased meat consumption, thereby extending our life span.

In the war against bacteria, viruses and other microbes that seek to invade our tissues, the human host defense system brandishes two powerful weapons: the innate immune system and the adaptive immune system. The innate system is the first responder. It mobilizes immediately at the scene of an attack or injury to eliminate pathogens and heal damaged tissue, and it essentially responds in the same way to all threats. The adaptive system, in contrast, kicks into gear more slowly, customizing its response to particular pathogens. In doing so, it creates an immunological memory that confers lifelong protection against the invader.

The inflammatory response is part of the innate immune system. It goes to work when tissues suffer damage from microbes, traumatic wounds, injuries or toxins, and, as Finch points out, physicians have long recognized its hallmarks. Some 2,000 years ago Aulus Cornelius Celsus, a Roman medical author, described four cardinal signs of inflammation—heat, redness, swelling and pain. The heat, Finch explains, comes from mitochondria, the power plants of our cells, which begin releasing energy as heat. It acts as a form of sterilization "because many bacteria are unable to grow when the temperature rises above 40 degrees Celsius," he adds. The swelling, on the other hand, results as damaged cells release chemicals that prompt blood cells to leak fluids into nearby tissues, thereby isolating the injured area from contact with healthy tissues.

Finch began examining the human-specific changes in genes related to host defense. He was quickly struck by the changes that had affected the apolipoprotein E (*APOE*) gene. This important gene strongly influences the transport and metabolism of lipids, the development of the brain and the workings of the immune system. It has three primary, uniquely human variants (alleles), of which *APOE* e4 and *APOE* e3 are the most prevalent.

APOE e4's DNA sequences closely resemble those in chimpanzee *APOE,* strongly suggesting that it is the ancestral human variant that emerged near the beginning of the *Homo* genus more than two million years ago and thus may have had the earliest effect on our longevity. Differing in several critical amino acids from the chimp version, *APOE* e4 vigorously ramps up the acute phase of inflammation. It boosts the production of proteins such as interleukin-6, which helps to increase body temperature, and tumor necrosis factor–alpha, which induces fever and inhibits viruses from replicating. Equipped with this supercharged defense system, children in ancient human families had a better chance of fighting off harmful microbes that they unwittingly ingested in food and encountered in their surroundings. "When humans left the canopy and went out onto the savanna," Finch notes, "they had a much higher exposure to infectious stimuli. The savanna is knee-deep in herbivore dung, and humans were out there in bare feet."

Moreover, early humans who carried *APOE* e4 most likely profited in another key way. This variant facilitates both the intestinal absorption of lipids and the efficient storage of fat in body tissue. During times when game was scarce and hunting poor, early *APOE* e4 carriers could draw on this banked fat, upping the odds of their survival.

Even today children who carry *APOE* e4 enjoy an advantage over those who do not. In one study of youngsters from impoverished families living in a Brazilian shantytown, *APOE* e4 carriers succumbed to fewer bouts of diarrheal disease brought on by *Escherichia coli* or *Giardia* infections than noncarriers did. And they scored higher on cognitive tests, most likely as a result of their greater absorption of cholesterol—a dietary requirement for neurons to develop in the brain. "So this would have been adaptive, we think," Finch remarks.

A DEFERRED COST

ALL TOLD, *APOE* e4 seems to be a key part of the puzzle of human longevity. Ironically, now that we live longer, this gene variant appears to double-cross us later in life. Its debilitating effects became apparent only as our human ancestors increasingly survived to middle age and beyond. In Lima, Finch and an international team of cardiologists, radiologists, biologists and anthropologists are now searching for traces of these afflictions in the preserved cardiovascular tissues of ancient adult mummies.

Inside the crowded imaging unit in Lima, Finch hovers over a technician's computer. It has been a long, trying morning. Several of the mummy bundles transported to the unit are too large to fit into the CT scanner. Others, when scanned, reveal little more than skeletal remains, raising doubts that the preservation of human tissue in the bundles will be adequate for the study.

But no one is giving up. On the screen is a crisp, three-dimensional CT scan of a bundle just wheeled in from the van. Hunching forward, cardiologists Gregory Thomas of Long Beach Memorial Medical Center in California and Randall C. Thompson of the University of Missouri School of Medicine–Kansas City scrutinize an anatomical landscape rendered strangely foreign by centuries of decay and desiccation. As the technician scrolls up and down the image, the two cardiologists gradually pick out preserved soft tissue and the snaking trails of major arteries. The relief in the room is palpable. Then, unable to resist, the two cardiologists take a quick preliminary look along the arteries for small, dense, white patches—calcified plaque that signals an advanced stage of atherosclerosis, or hardening of the arteries, the leading cause of fatal heart attacks and strokes. The individual has clearly calcified arteries.

Cardiologists have traditionally regarded atherosclerosis as a disease of modern civilization. Contemporary behaviors such as smoking cigarettes, eschewing exercise, dining on high-calorie diets and packing on the pounds are all known to increase the risk of hardened arteries. Moreover, several recent studies point to an emerging atherosclerosis epidemic in the developing world, as societies there grow more affluent and increasingly embrace a modern, Western lifestyle. Yet in 2010 Thomas and a group of his colleagues decided to test the idea that atherosclerosis is a disease of modern, affluent life by taking CT scans of ancient human mummies and examining their arteries.

The team started in Egypt, with 52 mummies dating between 3,500 and 2,000 years ago. Biological anthropologist Muhammad Al-Tohamy Soliman of the National Research Center in Giza estimated the age at death for each individual, based on an examina-

MODERN HUNTER-GATHERERS such as the Hadza of Tanzania live in natural environments filled with parasites and pathogens, just as chimpanzees do. Yet they live far longer than chimps—perhaps because of genes that adapted humans to eating meat.

tion of dental and skeletal development. Then the medical team pored over the scans. Discussing the images during weekly Skype calls, they identified cardiovascular tissue in nearly 85 percent of the mummies. To their surprise, 45 percent of these had definite or probable atherosclerosis—clear evidence that one ancient population suffered from the disease. "We were [also] a bit surprised by just how much atherosclerosis we found in ancient Egyptians who were young," recalls team member James Sutherland, a radiologist at the South Coast Radiologic Medical Group in Laguna Hills, Calif. "The average age of death was around 40."

When their paper came out in the *Journal of the American College of Cardiology* in the spring of 2011, Finch contacted the team immediately, proposing a new explanation for the high levels of atherosclerosis detected in the study. The ancient Egyptians, Finch noted, were no strangers to pestilence and infection. Previous studies showed that many ancient Egyptians were exposed to a wide range of infectious diseases, including malaria, tuberculosis and schistosomiasis (an ailment caused by tiny parasitic worms found in contaminated water). *APOE* e4 carriers, with their enhanced immune systems, tended to survive many childhood infections. But they experienced decades' worth of chronic high levels of inflammation in the pathogen-rich environment—levels that are now linked to several deadly diseases of old age, including atherosclerosis and Alzheimer's. Indeed, the arterial plaques that characterize atherosclerosis seem to accumulate during inflammation and wound healing in the vascular wall. "And while it might be pushing it to say the senile plaques of Alzheimer's are some form of scab, like the plaques on artery vessels, they have many of the same components," Finch suggests.

Thomas and his colleagues asked Finch to join their team. Together they decided to gather more data, examining the cardiovascular tissues of ancient mummies from a wide range of cultures. The Egyptians in their first study likely came from affluent upper classes that could afford mummification: such individuals may have exercised rarely and dined frequently on high-calorie foods. So the team expanded the study to other, very different cultures. They examined existing CT scans of ancestral Puebloan mummies from Utah and century-old Unangan mummies from Alaska. In addition, they analyzed the scans they had taken of pre-Hispanic mummies from coastal Peru. Those individuals dated to as early as 1500 B.C.

This past March the team published its findings in the *Lancet*. Among the 137 examined mummies, 34 percent had probable or definite atherosclerosis. Significantly, the scans revealed the disease in all four ancient populations, including the hunt-

NAFTALI HILGER *Redux Pictures*

ing-and-gathering Unangan people, who ate a largely marine diet. The findings clearly challenged the idea that atherosclerosis was a modern disease and pointed to another explanation. "The high level of chronic infection and inflammation in premodern conditions might have promoted the inflammatory aspects of atherosclerosis," the team wrote.

Perhaps, Finch says, the ancient gene variant that ramped up our inflammatory response and boosted the chances of our survival to the age of reproduction—*APOE* e4—came with a steep, deferred cost: heart attacks, strokes, Alzheimer's and other chronic diseases of aging. In fact, *APOE* e4 appears to be a classic case of something biologists call antagonistic pleiotropy, in which a gene has a strong positive effect on the young and an adverse impact on the old. "I think these are very intriguing ideas," says Steven Austad, a biologist and gerontologist at the University of Texas Health Science Center at San Antonio. "And what evidence we have supports them."

The findings clearly challenged the idea that atherosclerosis was a modern disease and pointed to another explanation.

REFINING IMMUNE RESPONSE

RESEARCH ALSO POINTS TO other gene variants that contributed to our longevity. At roughly the same time that *H. sapiens* emerged in Africa some 200,000 years ago, a second major *APOE* variant emerged. This allele, known as *APOE* e3, enhanced health among adults in the 40- to 70-year-old range and helped to slow the aging process, and today it has a prevalence of between 60 and 90 percent in human populations. As Finch points out, *APOE* e3 carriers produce a less vigorous inflammatory response than those with the ancestral variant. Moreover, they appear better adapted to meat- and fat-rich diets. Generally speaking, they have lower blood cholesterol and are less prone to the diseases that strip the old of their vitality: coronary heart disease, cognitive decline and Alzheimer's. Indeed, carriers of the more recent variant enjoy life expectancies as much as six years longer than their *APOE* e4 neighbors. "*APOE* e3," Finch notes, "may have been a factor in the evolution of long life spans."

APOE is not the only gene linked to the evolution of human longevity, however. At U.C. San Diego, Ajit Varki, a professor of medicine, and his colleagues are investigating several other genes that may have undergone changes that boosted our chances of survival and extended our lives. Varki's research focuses on the *SIGLEC* genes that play key roles related to host defense. These genes express proteins that straddle our cell membranes and act a little like sentries. Their function "is to recognize friends, not foes," Varki explains. It is no easy matter. To fool these sentries, infectious pathogens evolve camouflage consisting of proteins that mimic those borne by "friends."

In 2012 Varki and his team published a study in the *Proceedings of the National Academy of Sciences USA* that identified two key changes in these genes that dated to at least 200,000 to 100,000 years ago and that honed our ability to fight off pathogens. One change produced a new human variant of the ancestral primate gene *SIGLEC 17*. This variant, however, was nonfunctional. A second event deleted the ancestral gene *SIGLEC 13* entirely. To better understand these changes, Varki and his colleagues experimentally resurrected the proteins once expressed by *SIGLEC 13* and *17*. Both ancestral proteins, they discovered, had been "hacked" by pathogens responsible for two life-threatening infections in babies: group B *Streptococcus* and *E. coli* K1. So as natural selection began weeding out these compromised genes from our genome, the odds of survival rose in human infants.

Such findings add new fuel to the hypothesis that pumped-up immune systems played an important role in lengthening human lives. "Our immune systems went through a lot of changes," Varki says. And as geneticists and biologists continue to investigate the uniquely human part of our genome, many are starting to look for other gene variants and genetic events that contributed to our long lives today.

Yet already the findings are giving some researchers pause for thought. Public health messages have long warned that lifestyle choices such as couch-potato evenings and calorie-rich diets are largely to blame for the high incidence of atherosclerosis, heart attacks and strokes. But the new research—particularly the studies on ancient mummies—suggests that the picture may not be quite so simple. Our DNA and an overcharged immune system may well contribute to the development of such diseases. "So maybe we have a little less control over atherosclerosis than we thought," muses cardiologist Thompson. "Maybe our mental framework should be shifted." And perhaps, he adds, researchers should be looking for undiscovered risk factors.

The new findings are also raising a fundamental question about human longevity. Can we, or should we, expect the trend toward longer lives to continue? Some scientists have predicted that babies born after 2000 in countries where life expectancy had already been high—including the U.S., Canada, the U.K. and Japan—will live to 100 years of age. Finch is quietly skeptical, however. The emerging trend toward obesity in many human populations and toward environmental deterioration brought about by climate change, he says, could well affect human longevity negatively and throw a major wrench into the works. "I think there is a reason to be cautious about that," Finch concludes. "But time will tell." SA

MORE TO EXPLORE

Evolution of the Human Lifespan and Diseases of Aging: Roles of Infection, Inflammation, and Nutrition. Caleb E. Finch in *Proceedings of the National Academy of Sciences USA,* Vol. 107, Supplement No. 1, pages 1718–1724; January 26, 2010.

Atherosclerosis across 4000 Years of Human History: The Horus Study of Four Ancient Populations. Randall C. Thompson et al. in *Lancet,* Vol. 381, No. 9873, pages 1211–1222; April 2013.

SCIENTIFIC AMERICAN ONLINE
Compare human life span with that of other species at
ScientificAmerican.com/oct2013/life-span

STATE OF THE WORLD'S SCIENCE 2013

CROSSROADS OF INVENTION

Many of us think of invention as something that springs from an individual mind. It's a romantic view, but it bears little relation to the creative process behind the technologies that are shaping our world. That process is increasingly collaborative—not so much a single lightbulb going off in someone's head as many lightbulbs in a social network of diverse minds. The growing connectedness of the world and the rising contribution of scientists and engineers from all continents have broadened the possibilities for human creativity. This special section celebrates these developments and reports on some of the challenges they present. *—By the Editors*

IN BRIEF

Big corporations used to midwife good ideas from the research laboratory to the marketplace, but in the future that task will increasingly fall to a partnership of governments, commercial firms and universities (*page 58*).

To get different nations and institutions collaborating effectively on generating new technologies, we need new rules (*page 60*).

China is a rising star when it comes to innovation, but a closer look reveals that much of that work takes place in the labs of multinational corporations operating on Chinese soil (*page 62*).

Even though nations may differ in their levels of technological output, it is possible to compare how efficient they are at exploiting scientific research (*page 64*).

Mexico has difficulty translating its vibrant research into commercial technology, but the current government is trying to change that, in part by luring expat scientists back home (*page 66*).

Illustrations by Kotryna Zukauskaite

SCIENCE POLICY

WHO WILL BANKROLL THE NEXT BIG IDEA?

Miniature robots, personalized drugs and other potentially life-changing technologies lie waiting in the laboratory, lacking support. Here's how to fix the problem

By David J. Kappos

OUR MODERN WORLD is blessed with a wide array of products and services, health care options and medical treatments, gadgets and indulgences, all of which arrive on the scene with a rapidity that few of us can absorb. We find ourselves surprised and amazed by these wonderful innovations, and then we come to depend on them. What did we do before we had GPS, camera phones, brain scans and laser eye surgery?

The things that give us comfort and convenience and that improve our safety and health are the fruits of basic discoveries made decades ago in materials, software, computation, biology, chemistry and information technology, among other fields. And the rate at which new discoveries emerge from academic and government laboratories shows no sign of slowing. By such measures as academic papers and patent filings, science output continues to run as strong as or stronger than at any previous point in history. Moreover, with China, India and other nations coming onto the research scene in a big way, there is every reason to anticipate more great science in the future.

Great science does not automatically translate to world-beating technology, however. That transition requires time, money and patience—commodities that are lately in short supply. Indeed, the traditional ways of moving discoveries out of labs and into real-world applications have come under a good deal of stress in the past generation. Unless we address this shortfall, our bright prospects will not come to pass. We are, in many ways, living off the success of yesterday's investments.

Sources of funding and effort have grown tenuous at two crucial and costly steps in the path from lab to marketplace: at the early stage, when new scientific concepts are being applied to promising (but speculative) practical uses, and at the late stage, when a technology is making the transition to an actual product that has to be tested and perfected for market introduction. The vehicles for moving basic research through these twin valleys of death used to be the province of big corporate labs, but these institutions have largely ceased to perform that role. Venture-capital firms have not picked up the slack but instead have opted for "de-risked" prospects that are significantly downstream from the output of basic research labs.

This trend has put a squeeze on innovation across the board. Raw technology requires substantial investment to shepherd it into the marketplace. The payoff is often uncertain. Communications and green technologies—two key areas—are particularly vulnerable to rapid copying in ways that intellectual-property laws often cannot address. Translational R&D in general presents a less attractive business proposition than do downstream investments, in which the major challenges have already been overcome. Unfortunately, shortcuts to pushing breakthroughs forward are few and far between.

The crisis we now face is an opportunity to build a more open, freewheeling and bottom-up support system for the long march from lab to marketplace—one that may ultimately be more robust and better suited to the technologies of our age. Partnerships among governments, universities and corporations will have to replace the corporate largesse of old. To pull this off, we need a new culture of innovation, in which many smaller players work in concert to keep the pipeline of ideas flowing.

SIRI AND OTHER "LATENT OPPORTUNITIES"

AMERICAN SCIENCE and R&D constitute a dominant force on the world. From 1996 to 2011 the number of citable documents in scientific publications, including articles, reviews and conference proceedings produced by U.S. researchers, grew from roughly 310,000 a year to approximately 470,000 a year—far more, in absolute terms, than those of any other nation and at a faster growth rate than those of any nation other than China. During the same period, the percentage of published papers that list collaborators from the U.S. and at least one other country has also climbed, from about 22 percent to nearly 30 percent, illustrating, in part, the growth of international joint development—a product of better communication and data sharing. These numbers are strong, but behind them there is cause for worry.

To understand why, consider Siri, the cheeky iPhone assistant that emerged in 2011. Siri's roots go back to a $150-million, five-year, government-funded Defense Advanced Research Projects Agency initiative. Led by SRI International, it had 22 partners, including the Massachusetts

Institute of Technology, Carnegie Mellon University and Stanford University. SRI continued to develop the technology before spinning it out as a stand-alone company with venture-capital backing. By the time Steve Jobs bought the firm for Apple in 2010, Siri had absorbed \$175 million and seven years of development.

Siri is much more than a novelty for smartphones. The computing advances necessary to understand, process and respond to spoken-word queries regarding the location of the nearest Starbucks could soon be answering far more weighty questions. Imagine being able to consult a Siri-like tool about the lump you just found in your breast and having confidence in the answer. Such latent opportunities often become apparent during the course of moving a research idea through product development.

The case of Siri shows how what may seem like a simple path from R&D to marketplace can be long and winding. Larger-scale innovations in clean energy and pharmaceuticals often require decades of effort and a billion dollars or more in investment. Many of tomorrow's potential society-altering technologies currently lie waiting, full of promise but lacking support. Personalized drugs, which target individuals and their ailments, could one day alleviate great suffering. Yet the enormous cost and time to develop and test such specialized formulations under our regulatory regime make the investment a difficult sell. Advanced miniature robots, which could be inserted into the body to remove plaque from arteries, are another technology in waiting. Miniaturized, unmanned flying vehicles, currently a lab curiosity, could play a big role in advanced weather prediction or air-quality monitoring. As federal research dollars shrink and corporate labs focus on near-term product development, who will fund these technologies?

THE LEGACY OF BIG CORPORATE LABS

IN THE MID- TO LATE 20TH CENTURY the great corporate research labs served as a bridge from research to marketplace. One of the last important examples of corporate funding is strained silicon, the technology we have to thank for the amazing increase in performance of microprocessors in the past decade or two. Strained silicon is a technique for increasing the efficiency of silicon-based electronics; it involves depositing germanium onto silicon such that the space between silicon atoms grows, increasing circuit performance. Strained silicon started as an idea in a Cornell University lab in the late 1980s, then caught the attention of researchers at AT&T Bell Laboratories, who wanted better semiconductors for telephone switches. The company invested significant resources in this speculative technology even though the payoff was unclear. In 1996 the lead researcher, Gene Fitzgerald, then at M.I.T., formed Amberwave Technologies to commercialize it. From there it took another seven years and millions of dollars more before Intel unveiled its strained silicon–based "Prescott" Pentium 4 processor.

Examples abound of technologies that shape our lives that would not have seen the light of day without support from big corporate labs. Hydraulic fracturing, or "fracking," dates back to the 1800s but only found widespread commercial use after Stanolind Oil, part of Standard Oil of Indiana, took up the technology in the 1940s. It took decades of further development before the technology could tap natural

gas from previously unreachable reserves. The circuitous route of 3-D-printing technology started as ink-jet research at Siemens in the 1950s, which wound through Stanford's medical school, IBM, paper company Mead, and, eventually, Hewlett-Packard and other printer manufacturers.

The road from laboratory research breakthrough to practical implementation to marketplace success is long and unpredictable and requires numerous iterations. Today's product-focused companies cannot be expected to bear the expense of this undertaking. But it is crucial that we find a way to do so. Indeed, the withdrawal of big corporate research is already being felt, both in the U.S. and elsewhere.

SHORT-TERM PRESSURES

SHORT-TERM MARKET PRESSURES have already weakened investment in solar technologies and transportation electrification. In the information and communications technologies, the National Academy of Sciences has warned that "federal long-term basic research aimed at fundamental breakthroughs has declined in favor of shorter-term, incremental, and evolutionary products whose main purpose is to enable improvements in existing products and services." The U.S. no longer leads the world in "R&D intensity," the Telecommunications Industry Association notes, having fallen to eighth place among the Organization for Economic Co-operation and Development countries. "Over the past 35 years," it says, "the U.S. federal government has been the primary sponsor of basic research … as all but a few corporate R&D laboratories no longer were able to afford the high costs and risks of basic research. Their corporate mandates required shorter-term R&D with faster paybacks."

The story is similar in Europe and Asia. Large corporate funding sources for translational research have diminished or remained flat in those countries, mostly from the same short-term pressures and belt tightening. At least the U.S. has some venture capital to cushion the blow—Europe and Japan are not so lucky.

The rise of China and India has generated a new dynamic. Those countries could reinvigorate research, but they might also pose a threat to established technological nations. China could invest billions of dollars of state-controlled capital on product research stemming from basic research conducted in the U.S., Europe and Japan, thus reaping the resulting jobs and economic prosperity. Patent rights usually expire by the time such research reaches the marketplace, so China would not have to violate any intellectual-property rights. In fact, because commercializing basic research produces intellectual property in its own right, China could wind up demanding royalties from inventions stemming from research in other countries.

India's strategy is no more reassuring. It has effectively nationalized important patents to the benefit of its drug industry. Whether it will extend this approach beyond health care remains to be seen.

There is a positive view of the rise of

THE POWER OF MANY MINDS

To tap the world's vast and growing potential for new ideas, we need new rules

IN THE CENTRAL AFRICAN rain forest, a team of researchers and students from the U.S., Cameroon, Gabon, the U.K., Germany, France and the Netherlands is creating a conservation plan for the region that takes climate change and regional economic development into account. This group, funded by the U.S. National Science Foundation, includes biologists, agricultural experts and social scientists.

Collaboration among people from many different disciplines and nations—sharing goals and resources—is becoming the new normal in science and engineering. Diversity in research teams accelerates innovation, perhaps because researchers with different backgrounds see the same problems through different lenses, and together they can correct one another's hidden biases.

Underneath this growing unity and opportunity, however, there is some tension. A nation gears its public spending for research and education to reflect its own priorities, but the knowledge these efforts yield is not confined to any national boundary. In a borderless, Internet-connected world, how can each nation ensure the sustainability and survival of its engine of innovation? How do nations that must collaborate with one another agree to common principles of engagement, standards for quality of output and free access to that output? And who will ensure that nations adhere to such agreements? These are the urgent science policy questions of our day. Without a way to develop principles of engagement, global science will be hamstrung.

Scientists who work in international teams, especially those new to the global research enterprise, need standards of ethics in research practice and other clear norms about how research is conducted. These include ways of judging the merit of research proposals and ensuring that scientists can share and archive the results of their research while ensuring privacy, confidentiality and intellectual-property rights. We need clear policies and a sustainable financial model for open access to publications and data that involves stakeholders at universities, libraries, professional societies and publishers.

The world's research funding agencies and governments have begun to address these issues. In 2012 the Global Research Council (GRC), a group made of heads of science and engineering funding agencies from nearly 50 countries around the world, met to create common principles for merit review. This group is developing shared norms from the perspective of the institutions that fund scientific research and is now exploring ways of engaging research performers—most notably, the world's great research universities—in the discussions.

This effort to create a consistent and harmonious framework in which diverse scholars can work collaboratively constitutes an important step toward establishing a global culture of innovation. As educators and researchers, we owe it to the taxpayers of the world to generate maximum innovation from public research spending. The team in the Central African rain forest needs standards to effectively accomplish its scientific and social mission. So do all the others who depend on science to benefit our communities and our lives. *—Subra Suresh*

***Subra Suresh,** former director of the National Science Foundation and founding chair of the Global Research Council, is president of Carnegie Mellon University.*

China and India, however. Because those nations support a growing fraction of the world's scientists, it is only logical that they will produce more breakthroughs. Consumers everywhere will benefit. Even if China, say, takes U.S. research and turns it into products, that would be better than if no one did so.

FILLING THE RESEARCH GAP

IN THE ABSENCE of big corporate sponsors, the U.S., for one, must recalibrate its approach to support the transition of research from lab to marketplace. We will have to make some sacrifices in our long love affair with free-market competition and face up to the fact that parts of the hard, costly, uncertain process of innovation require major support from federal, state and local governments.

The recent furor over the failures of solar firm Solyndra and hybrid-battery maker A123 Systems has given federal investment in technology commercialization a bad name, but this kind of investment must continue. Washington needs to spread its bets and fund a wide range of entities—from government research labs to privately funded technology start-ups that are well positioned to turn research into products and services. After all, the Internet grew out of research in the Department of Defense, GPS positioning came from military research, and flame-resistant clothing now used by firefighters originated at NASA. When the National Science Foundation celebrated its 60th anniversary in 2010, it listed 60 discoveries supported from its coffers: magnetic resonance imaging, fiber optics, supercomputers and cryptography, to name just a few.

Federal support is only one step. We also must encourage partnerships that combine the public resources of our government agencies and major research universities with investments of time and funding from private industry.

This hybrid public-private approach is not new, but it has so far been mostly restricted to small, fringe projects, many of them underfunded. Technology-transfer offices at elite universities are not well integrated into the primary operations of the academic community. State-organized collaborations between publicly funded researchers and private industry to grow new companies–and high-value jobs–are not yet broad enough to encompass investments stretching to early stages.

Some useful models are emerging, however. Research for Advanced Manufacturing in Pennsylvania (RAMP) puts Carnegie Mellon and Lehigh University together with Pennsylvania companies with the aim of discovering new technologies and accelerating the flow of knowledge between university research institutions and private industry. RAMP investments include next-generation research on industrial applications of 3-D-printing technologies and a manufacturing process for blood plasma–based biomaterials.

Other states are also creating frameworks to encourage partnering. For fiscal year 2012, Ohio allocated $25 million in funding for world-class public-private research labs that focus on advanced materials, regenerative medicine, fuel cells and energy storage, and alternative energy. In 2005 the state of Texas established the Emerging Technology Fund to provide matching funds to private firms that want to commercialize research originating from Texas universities or the NASA Johnson Space Center in Houston.

MONEY FOR THE LONG HAUL

WE NEED MORE such collaborations. How do we encourage both public and private actors to engage in them? The National Advisory Council on Innovation and Entrepreneurship, formed by the U.S. Department of Commerce, brought together thought leaders from industry, venture capital and universities to address this question. The council came up with a number of recommendations to encourage these groups to cooperate. Federal agencies can foster opportunities for high-risk innovative research. Industry and universities can strengthen their strategic investments in advancing technologies of mutual interest. And they can all start programs to connect university faculty and students to potential industry partners, entrepreneurial mentors and sources of "proof of concept" funding.

Federal agencies could help universities incorporate innovation components into grant applications. Universities that use their intellectual property in collaborations with industry could be granted preferential tax treatment. At the same time, university technology-transfer offices could strive to maximize the benefit of discoveries to society rather than maximizing revenues to their university.

Our regulatory processes also need streamlining. In highly regulated but rapidly advancing industries such as green energy, regulations designed for the days when data were scarce and time-consuming to process put an unnecessary drag on innovators. Eliminating bottlenecks would speed things up and lower costs.

Europe and Asia have taken steps to establish incentives for innovators. France, China and Japan have adopted volume-based research tax credits, which reward companies for the sum total of their R&D activities. In contrast, the U.S. grants tax credits in piecemeal fashion, a cumbersome method that many American firms do not bother with. The continued development of the European Research Area, first launched in 2000 and relaunched in 2007 to focus efforts on a shared vision by 2020, has led to an increase in R&D investment and cooperation among European nations. Perhaps the U.S. could form a federated research organization for the Americas.

The idea behind these ideas is to change the culture into one that recognizes the value of investing for the long haul and creating sensible incentives. If we do this right, we will have built an innovation ecosystem that will continue to turn great science into transformative technology for another century. SA

David J. Kappos *was undersecretary of the U.S. Department of Commerce and head of the U.S. Patent and Trademark Office until joining the law firm Cravath, Swaine & Moore as partner earlier this year. He serves on the World Economic Forum's Global Agenda Council on the Intellectual Property System.*

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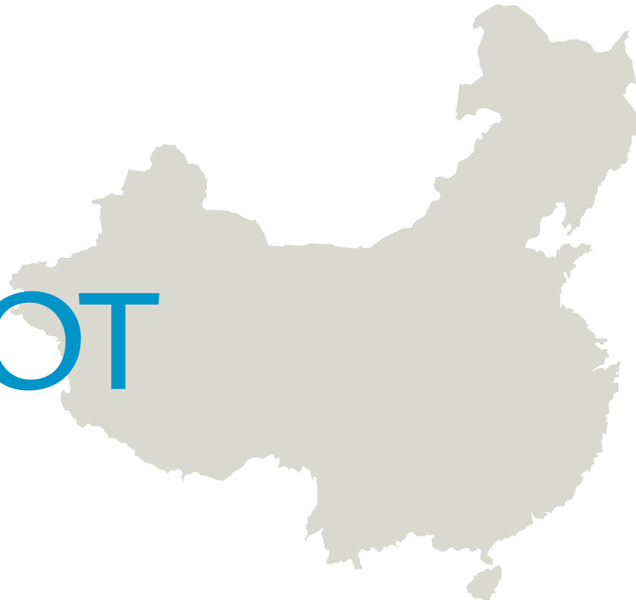
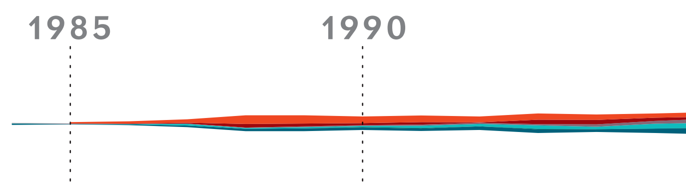
RESEARCH & DEVELOPMENT

THE POLYGLOT PATENT BOOM



Why China's surge in international patents marks the emergence of a new, international form of research and development



By Lee Branstetter, Guangwei Li and Francisco Veloso

COUNTRIES GENERALLY do not start creating much new-to-the-world technology until they are pretty wealthy—specifically, until their per capita output and income approach that of the world's richest countries. China is still quite poor. As recently as 2010, its per capita income was less than one-tenth that of the U.S. Yet according to the official data, Chinese businesses increased their R&D spending by 26.2 percent per year between 1996 and 2010. The number of patents that America's own patent office has granted to Chinese inventors rose 4,628 percent between 1996 and 2010. What is going on here?

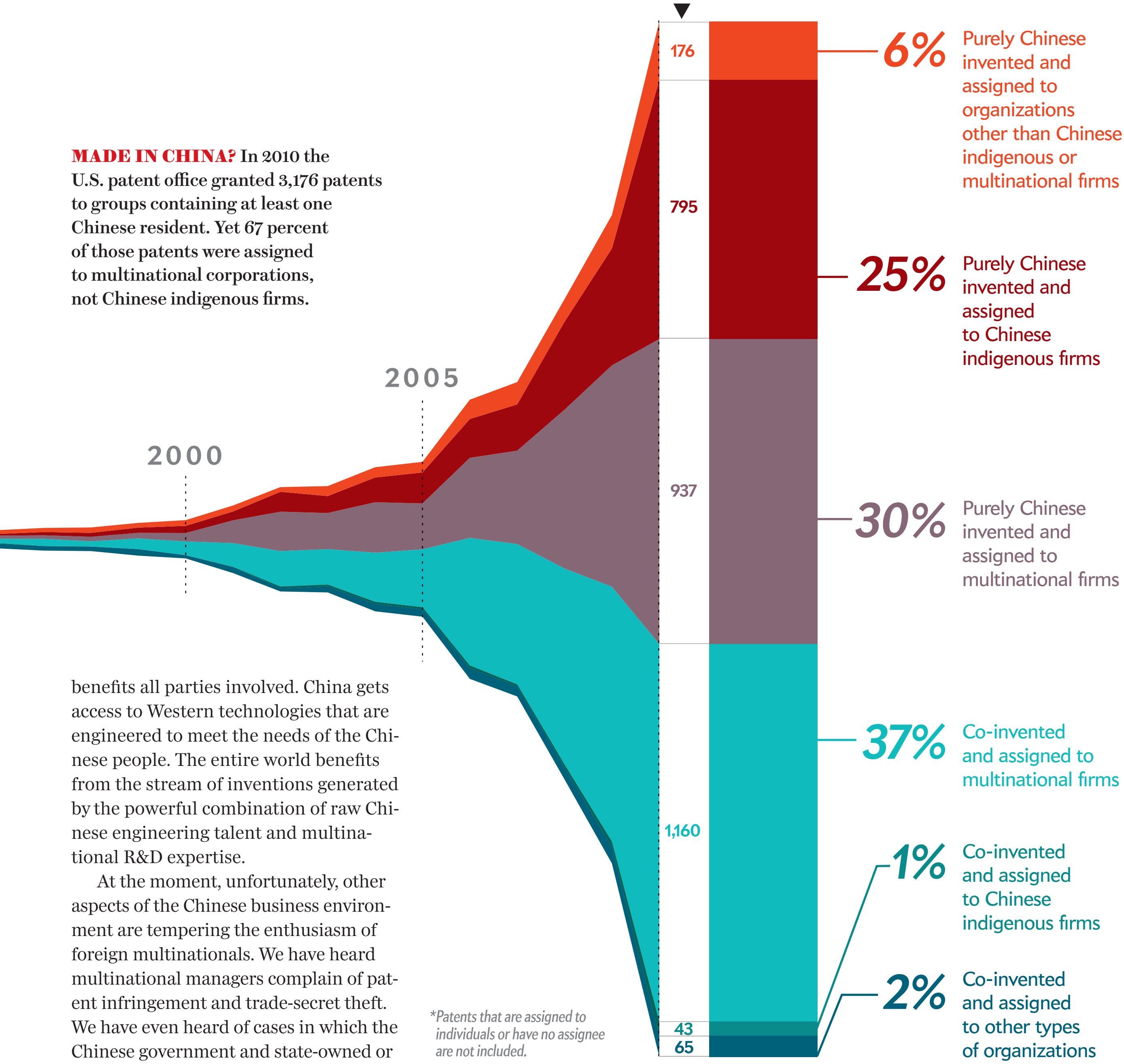
A close look at these patent filings reveals that multinational corporations, not Chinese firms, own the majority of the U.S. patents that were issued during this recent boom. In other words, Chinese indigenous companies still lag behind their multinational competitors in generating inventions that get patented in major foreign markets.

Compared with the rise of other Asian economies, China's situation is unusual. From the earliest days of their emergence as important innovation hubs, Japanese, Taiwanese and South Korean companies owned and produced nearly all the U.S. patents granted to inventors based there. Things went differently in China for a few reasons. First, China opened its borders more completely to foreign companies and did so earlier in its economic development than did many of its Asian forebears. Second, China's vast size and rapid growth motivated multinationals to establish research and development centers in China at an early stage, to ensure their success in this key emerging market. Third, the Internet made it possible for engineers based in China to collaborate on research projects with colleagues all over the world in something approaching real time. This set of circumstances has allowed for a more intense degree of research interaction between Chinese R&D personnel and their advanced regional counterparts than had been possible when Taiwan and South Korea were becoming innovative economies.

In our research, we have seen this direct international interaction traced out in the patent documents themselves. Most of the China-generated U.S. patents owned by multinationals are actually produced by international inventor teams, some members of which have addresses outside China. We refer to this phenomenon as international co-invention, and it is also a prominent feature of the patents granted to Chinese inventors by the European Patent Office.

International co-invention is not only focused on reengineering existing technologies for the Chinese market. Many multinationals now devote much of their China-based research manpower to producing new technologies for global markets. Viewed as a whole, this growing international research collaboration

MADE IN CHINA? In 2010 the U.S. patent office granted 3,176 patents to groups containing at least one Chinese resident. Yet 67 percent of those patents were assigned to multinational corporations, not Chinese indigenous firms.



*Patents that are assigned to individuals or have no assignee are not included.

benefits all parties involved. China gets access to Western technologies that are engineered to meet the needs of the Chinese people. The entire world benefits from the stream of inventions generated by the powerful combination of raw Chinese engineering talent and multinational R&D expertise.

At the moment, unfortunately, other aspects of the Chinese business environment are tempering the enthusiasm of foreign multinationals. We have heard multinational managers complain of patent infringement and trade-secret theft. We have even heard of cases in which the Chinese government and state-owned or state-sponsored companies pressure multinationals to transfer sensitive technology to unaffiliated Chinese "partners."

Nevertheless, we are already seeing evidence that international co-invention is emerging in India and in Eastern Europe, as well as in China. This phenomenon marks the emergence of something new in the world: an international division of R&D labor that links skilled engineers in emerging economies with the technological expertise of established multinationals. That is a good thing. In fact, it could be essential for confronting the enormous technological challenges facing the human race in the 21st century. SA

Lee Branstetter is an associate professor of economics and public policy at Carnegie Mellon University. Guangwei Li is a doctoral student at Heinz College at Carnegie Mellon. Francisco Veloso is a professor in the department of engineering and public policy at Carnegie Mellon and dean of Católica-Lisbon School of Business and Economics in Portugal.

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Graphic by Pitch Interactive

WORLD ECONOMICS

INNOVATION SCORECARD

How well do mature and emerging nations capitalize on science?

Since 2007 economists from Cornell University, INSEAD and the World Intellectual Property Organization (WIPO) have issued the annual Global Innovation Index (GII), a report that sizes up the innovative capacities and results of the world's economies. This year's report includes data on 142 economies, which represents 94.9 percent of the world's population and 98.7 percent of global GDP. How does one measure something as abstract as "innovation"? The GII researchers use 84 data points ranging from political stability to ease of starting a business to the number of Wikipedia edits originating there every year.

This year's big-picture findings: R&D spending has rebounded around the world after suffering in the wake of the global financial crisis. The same high-income usual suspects—the wealthiest European countries in particular—dominate the top of the list. The BRIC nations—Brazil, the Russian Federation, India and China—all slipped in this year's rankings. R&D spending is growing more quickly in emerging markets than in rich countries. And unexpected players such as Costa Rica, Uganda and Moldova are doing impressively well with comparatively little. SA

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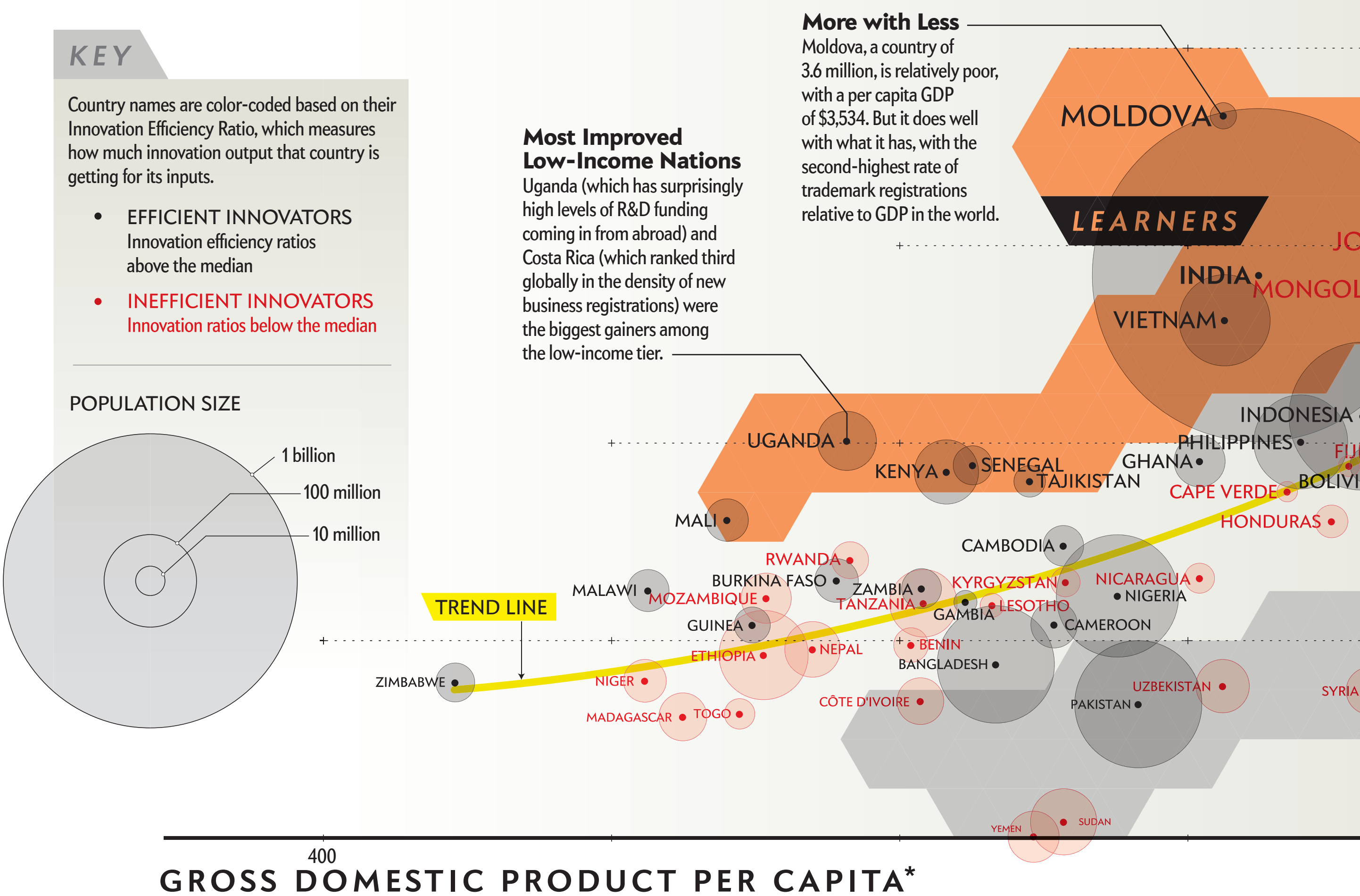

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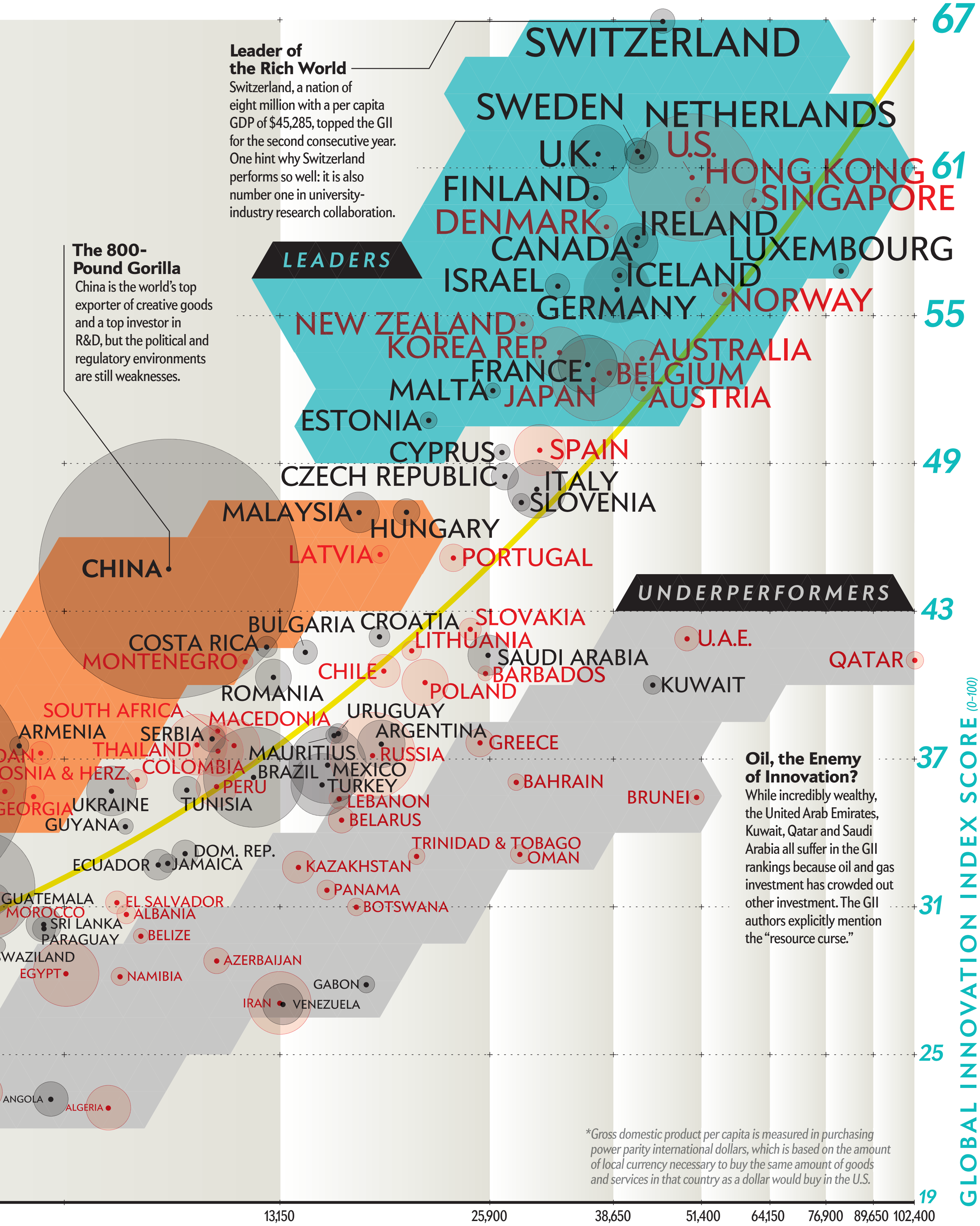
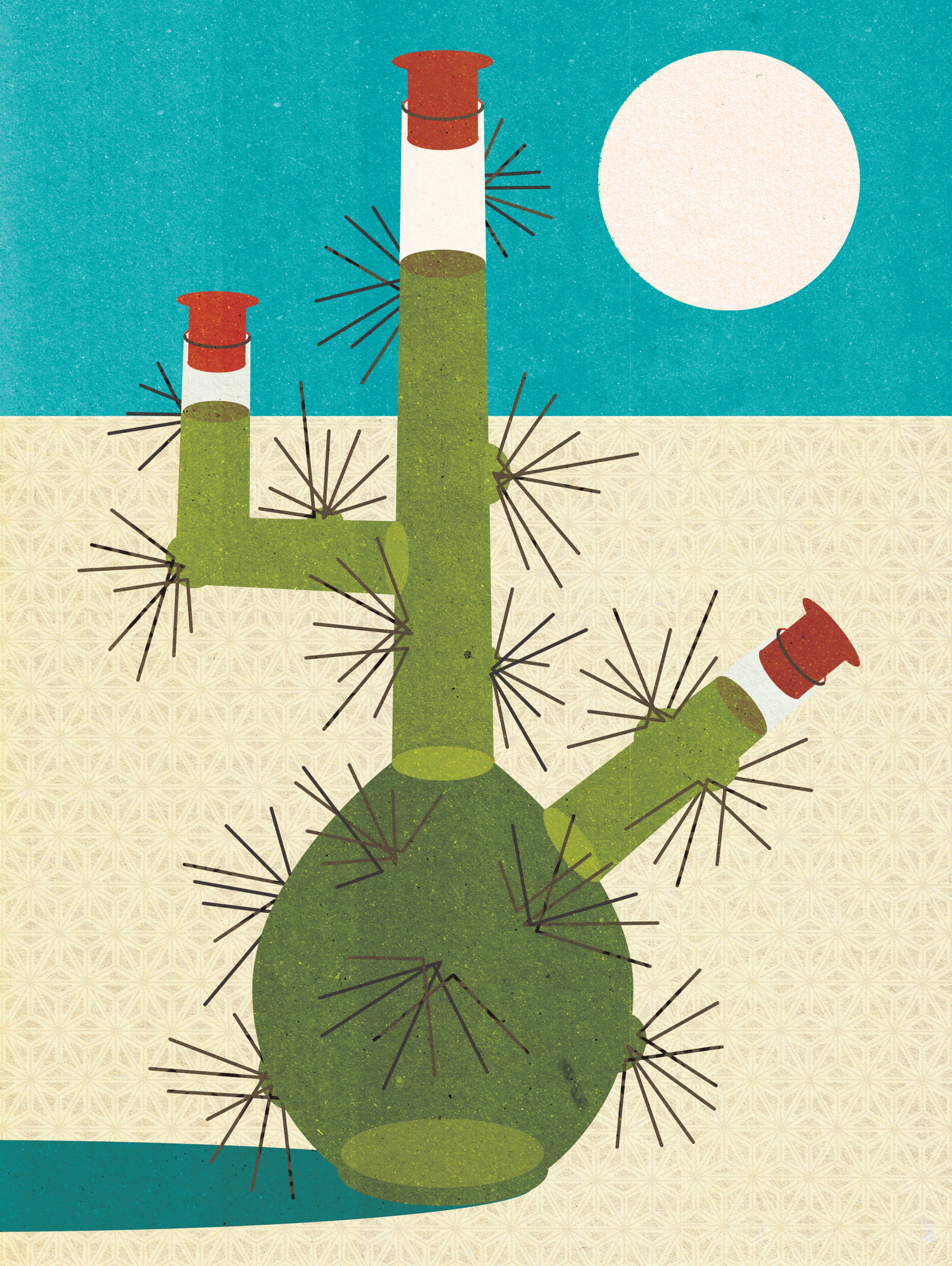


SOURCE: *THE GLOBAL INNOVATION INDEX 2013: THE LOCAL DYNAMICS OF INNOVATION*, EDITED BY SOUMITRA DUTTA AND BRUNO LANVIN. CORNELL UNIVERSITY, INSEAD AND WIPO, 2013



TECHNOLOGY TRANSFER

WHY CAN'T MEXICO MAKE SCIENCE PAY OFF?

The nation is poised to explode into the information economy—and yet stubbornly refuses to do so

By Erik Vance

IN 2008 IT SEEMED LIKE Enrique Reynaud had the world in his back pocket. A veteran professor of molecular biology at Mexico's largest and most important university, he was about to start his first company, Biohominis. It was a kind of Mexican 23andMe—a laboratory that could offer insight into a customer's genetic proclivity to hypertension, diabetes and other diseases.

In many ways, Biohominis was the culmination of Mexico's biotech tradition, which goes back to Norman Borlaug, who kicked off a green revolution around Texcoco. Biohominis was based in part on innovative applications of the polymerase chain reactions used in genetic testing and was developing techniques to identify cancers, metabolic problems, and viruses in humans and livestock.

To do this, Biohominis assembled a dream team of geneticists. María Teresa Tusié Luna, an expert in the genetics of type 2 diabetes—an epidemic whose proportions in Mexico rival only the U.S.—was an adviser. Isabel Tussié Luna, an expert in the genetics of brain damage who has published in *Nature Biotechnology,* was chief operations officer. And Eduardo Valencia Rodríguez, founder of one of Mexico's biggest construction companies that builds pharmaceutical facilities, was in charge of running the business side.

Even the Mexican government had gotten behind the firm. For years prior to its founding, government officials pri-

vately had been telling Reynaud that companies like Biohominis are exactly what Mexico needs to reposition itself as a technological leader rather than a source of cheap labor. The government even backed up this encouragement with cash, contributing $500,000 or so to kick-start the business.

It was not enough. Mexico, in the end, was cruel to Reynaud and his colleagues. Two years after getting its start, Biohominis filed for bankruptcy. The members of the dream team went their separate ways.

In almost every measurable way, Mexico's once dominant science institutions have stood still as those in other countries pass them by.

How could a company that had so much going for it come to such a disappointing end? The case of Biohominis shows how difficult it is to instill a culture of innovation in a country that in many ways is the antithesis of the open-minded, meritocratic Silicon Valley way of operating. Despite its vibrant scientific research community, Mexico so far has not managed to translate its know-how and talent into local products, technologies and start-ups. Mexico is not the only middle-income nation struggling to break free from a cycle of sweatshops and huge wealth disparities. But perhaps more than any emerging country, Mexico is and has been poised to explode into the information economy—and yet stubbornly refuses to do so.

VIBRANT AND BOGGED DOWN

MEXICO'S ECONOMY has baffled development experts for years. The National Autonomous University of Mexico (UNAM)—often credited with creating Mexico's middle class—is one of the biggest in the Western Hemisphere, with more than 300,000 students, and has a healthy research arm. According to government figures, 130,000 engineers and technicians graduate from Mexican schools every year. Mexican scientists invented an early color television and the birth-control pill and helped to identify the ozone hole.

And yet in almost every measurable way, Mexico's once dominant science institutions have stood still as those in other countries pass them by. Argentina and Chile are nipping at its heels. Brazil spends three times as much on science and technology, and its universities are now ranked higher than Mexico's. South Korea sends 10 times as many students per capita to U.S. universities, and Turkey publishes almost twice as much. Meanwhile a horrendous drug war has ripped the north of Mexico to shreds, corruption is rampant, and patents and new businesses are at a slow drip.

This schizophrenic quality of Mexican innovation—at once dynamic and bogged down—was a big part of recently elected Enrique Peña Nieto's presidential platform. He has promised a more technological Mexico, one that cultivates an innovation-focused, knowledge-based economy. He plans to start with cash—Mexico spends a paltry 0.4 percent of its gross domestic product on science and technology. The U.S. spends seven times as much of its GDP.

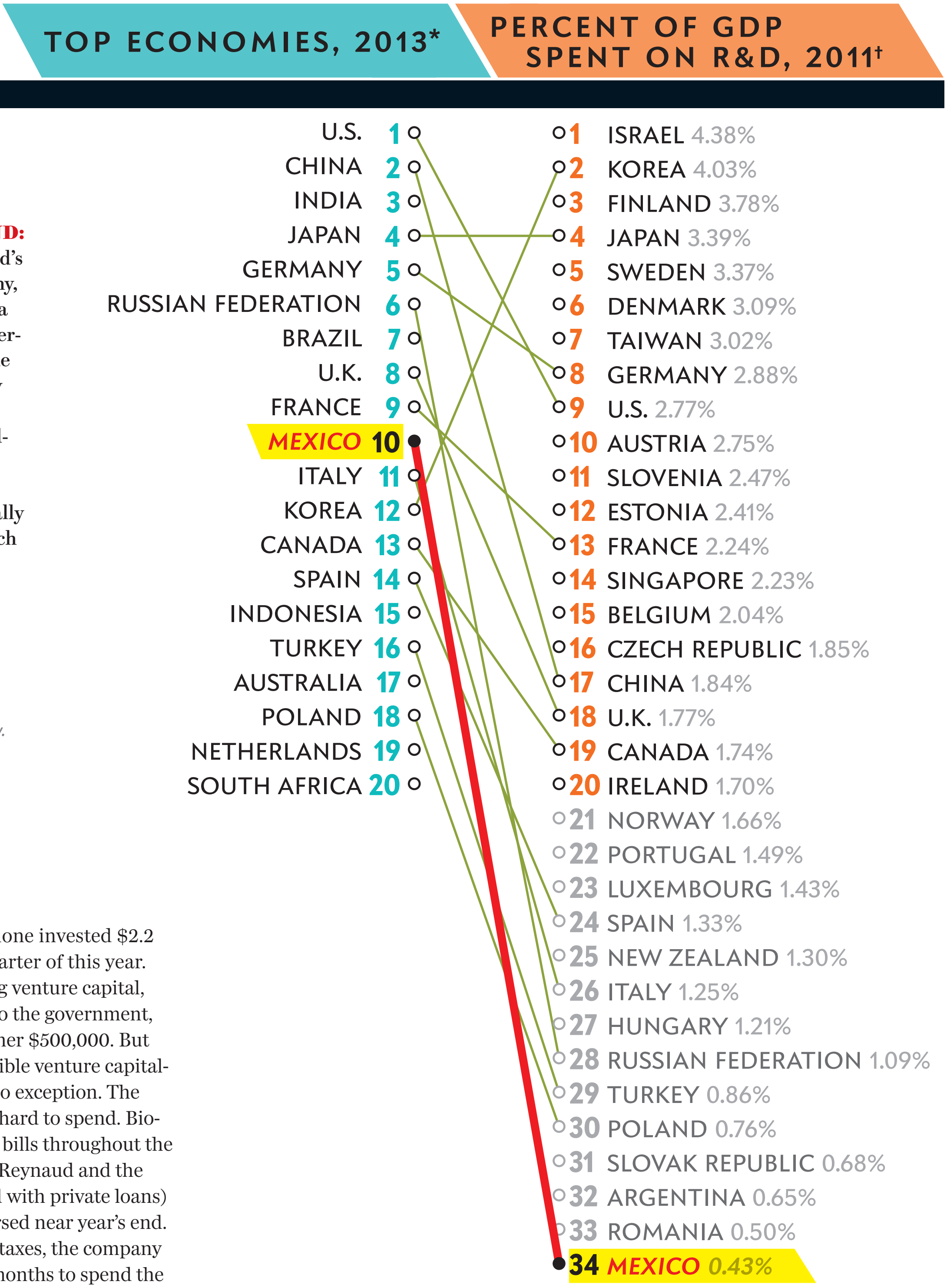
But Mexico's innovation dysfunction is deeper and more widespread than just money. Innovation in Mexico gets stopped in three different stages: at the beginning, when an invention is only a germ of an idea; in the middle, when scientists and engineers set out to form the company that will bring an idea to fruition; and at the end, when an idea fails and it is time to begin again. Biohominis ran into problems in the middle stage, so we will start there first.

STUCK IN THE MIDDLE

BY THE TIME REYNAUD and his partners had spent the money the federal government had given them, they were making money selling a few solid products. They looked to private investors to keep them afloat until they were stable. But there was no one to fund them. Most investment companies could not grasp what Biohominis had to offer. "When they hear 'technology,' they think we are in Bangalore and we are doing software. They want software factories because that's what they understand. They want trucking companies and logistic companies," Reynaud says. "They love service companies. If you want to get money from an investor in Mexico, get a crew for mopping floors—they understand that kind of business."

Lack of cash is not the main problem. Mexico's $1.2-trillion economy—the world's 10th largest—has seen remarkable repeated growth of at least 3.5 percent a year. Carlos Slim, the wealthiest man in the world, is Mexican. Yet the few companies that expressed interest wanted guarantees of 20 percent annual profit margins—a steep price in any market but especially hard for a start-up—or large ownership stakes.

The kind of financing that Reynaud was offered was not venture capitalism as we know it in the U.S. In California and elsewhere, venture capitalists are the glue that brings ideas together and the grease that keeps things moving. They understand the science of their field and make connections in labs and university departments. Crucially, they gamble on lots of companies at the same time—most of which will never make it—and simply walk away if they fail. Mexico's private funding is not set up this way. Today there are just 15 or so venture-capital funds in Mexico. This is an improvement on the two there were in 2008, but only four could be considered serious players. All told, the firms invested $469 million in 25 projects in



FALLING BEHIND: Mexico has the world's 10th-largest economy, and it is growing at a rate of at least 3.5 percent per year. Yet the country spends only a tiny fraction of its gross domestic product on research and development, even less than economically troubled nations such as Spain and Italy.

**According to the OECD Research and Development Statistics (RDS) database, which is made up primarily of OECD member countries. Economy ranking is based on 2005 purchasing power parity. Certain provisions apply.*

†Data for 2011 not available for several economies.

SOURCE: ORGANIZATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT'S RESEARCH AND DEVELOPMENT STATISTICS DATABASE *http://stats.oecd.org*

2011. The Bay Area alone invested $2.2 billion in the first quarter of this year.

Stymied in seeking venture capital, Reynaud went back to the government, which provided another $500,000. But governments are terrible venture capitalists, and Mexico's is no exception. The money was bizarrely hard to spend. Biohominis paid its own bills throughout the year (much of which Reynaud and the other owners covered with private loans) and then got reimbursed near year's end. To avoid horrendous taxes, the company had just a couple of months to spend the entire year's worth of money. It could spend that money only on lab research and not general operations. And even then, Biohominis had to pay taxes that would later be reimbursed.

Massive companies such as Nestlé or telecom giant Telmex can incorporate grants like this into bloated R&D budgets and could care less about payment schedules. But for a nimble start-up living month to month, these restrictions were death. Reynaud could not spend the money fast enough while simultaneously getting buried under debt to cover his operating costs.

Despite the support and expertise and a growing stream of income, Biohominis shut down for good in December 2012. In the end, it was not so much the product or the management or the market that killed it as a government that was clumsily trying to help. The death of Biohominis was slow and sad, bled out by cuts from 1,000 pieces of red tape.

"UNAM has incredibly good scientists. But there is nobody to make the

Graphic by Pitch Interactive

link, the bridge building and the matchmaking, who understands the technical side and then understands the business side. That's the uniqueness of the venture capitalists," says Carlos Santacruz, an investor who has worked in both Silicon Valley and Mexico.

STALLED AT THE START

IN SOME WAYS, Biohominis was lucky. At least it had investors and something of a business going before it ran aground. Many ventures do not even get that far, because they run into a cultural impediment: a mistrust of homegrown technology and an inferiority complex concerning their neighbors to the north.

When Mexican companies need research to solve a problem, they tend to look to U.S. or European companies for solutions. "There is this myth that has been created that we can't develop technology in Mexico," says Pilar Aguilar, director of Endeavor Mexico, the Mexican branch of the Endeavor Global organization, which promotes innovation in the developing world. "We've seen very innovative technologies based on chemical processes or in artificial intelligence. And the first reaction we get many times [from Mexican businesses] is, 'Really? Are we doing that in Mexico? Is that even possible?' We are used to thinking that the best technology comes from somewhere else."

Similarly, Mexican scientists with new ideas tend to start companies abroad before bringing them home. That is what Horatio Montes de Oca did. A few years ago Montes de Oca, a physicist whose undergraduate education was in Mexico but who is currently living in Ireland, came up with a material that he thought might be used in tendon or ligament repair and reconstruction (he declined to give specific details). He decided he wanted to develop the idea through a Mexican university laboratory in the state of Querétaro.

But the university had no idea how to work with him. There were no procedures or rules to partner with an outside entrepreneur, and it would take years to set them up. He got the same answer from other universities in Mexico. Montes de Oca, whose parents were academics, more or less just shrugged his shoulders. "The academic institutions in Mexico are not created and are not there to replicate [a capitalist] system," he says. "When you are an entrepreneur, you have to make a decision and say, 'This is not going to happen. I wish I could do it in Mexico, but I can't wait five years to develop it.'"

Eventually Montes de Oca partnered with a British lab to develop his invention. It is a predictable story—one of the hundreds of thousands of Mexican researchers living outside the country has a big idea and, in a fit of sentimentality, patriotism or homesickness, tries to bring the idea home. But a series of obstacles pushes them back to the U.S. and Europe.

> "We've seen very innovative technologies based on chemical processes or in artificial intelligence. And the first reaction we get many times [from Mexican businesses] is, 'Really? Are we doing that in Mexico? Is that even possible?'"

In most of Mexico, the idea that universities should help industry—either with research or by fostering new companies—is new and not terribly popular. In fact, professors are paid based on seniority and the papers they publish, with no incentives to patent or start businesses. And even if they patent, enforcement is so lax that another lab can just take the idea. As a result, most research is highly theoretical, and the government looks to other countries for things such as flu vaccines, as it did during the 2009 H1N1 outbreak.

Luis Marin, a UNAM geophysicist, sees this every day. In the early 1990s Marin helped to identify Chicxulub—a massive crater off the Yucatán Peninsula—as the impact site of the asteroid that killed the dinosaurs. Today he publishes more than three papers a year—eight times the university average, he says—and runs a side business contracting with companies such as Coca-Cola looking for groundwater for making soda. As his business has grown, his colleagues have ostracized him. After years of working with the corporation privately, he tried to bring the project under the umbrella of the university. But by the time every office took its cut, about half his budget was going to administrative fees. So he streamlined the idea and ran it directly through the office of the president. Colleagues lined up against him to say he was trying to cheat individual departments. After 23 years at the school, he got his first bad performance review, which determines his pay for the next year.

Shaking his head in his cozy office in the south of Mexico City, he says it is not clear he will be there for another year. He recalls that Harry Steenbock, the University of Wisconsin scientist who in 1923 irradiated foods, added vitamin D to them and helped to cure the disease

rickets, patented the technology and used the massive windfall for more research. "*That's* where we need to move. But if I want to spend some time on these things, I get punished. Forget breaking even—I get punished," he says. "There's no clear financial gain as a scientist to patent something. You make less money and are not well [regarded] by your peers."

RISK-AVERSE CULTURE

PERHAPS THE BIGGEST obstacle Mexico must overcome is an intolerance of risk. In California's Silicon Valley, failure is considered a stepping-stone to later success. In Mexico, "people here feel that when they start investing in companies that they need to be like the next big families of Mexico, where every investment is going to turn around and become one of the huge companies of Mexico," says Pablo Slough, head of Google Mexico. "It doesn't work that way. That's what I think is missing—that kind of middle-of-the-road, let's-bet-on-things attitude."

The Google office in Mexico is a small slice of dot-com California, bizarrely out of place in conservative Mexico. Slough is a smooth, charismatic speaker who dresses and acts every bit the Silicon Valley entrepreneur. He is Argentine by birth but invests regularly in Mexican companies almost as a matter of principle. Slough says, historically, the country's biggest companies have been either tied to government (such as oil giant Pemex) or are former government monopolies that subtly morph into corporate monopolies (such as Telmex). This skewed market, he says, creates an investment culture that irrationally expects guaranteed returns.

Recently Slough invested in a small outfit that created portable, inflatable playgrounds for children. When the company did not work out, he shrugged and moved on to the next investment. But he was shocked at what the other investors said to the two young Stanford University graduates who started the company. "They were berated," he says. "This risk of failure is a big deal here. In the U.S., you can start a company, it fails—who [cares]? Start another one."

Perhaps for this reason, the Mexican stock exchange has seen just 17 companies release initial public offerings in the past five years. In contrast, in the first half of this year, the New York Stock Exchange had released 85.

Absent or antagonistic investors, maddening red tape and an antirisk business culture are why Mexico has one of the most profound brain drains in the world. Mexico sends more undergraduates and grad students to the U.S. than any Latin American country. But when talent goes abroad, there is a chance it will not come back. One study suggested more than 70 percent of Mexican Ph.D.s end up leaving.

The Peña Nieto government has identified this problem. During the 2012 campaign, representatives said they planned to reach out to several active researcher/expat networks to enlist the help of Mexicans living abroad to either partner with them or even lure a few back home. Except at the very top universities and laboratories, Mexico cannot compete with the salaries and resources that scientists find in the U.S. "If I could work in a research center in Mexico that would allow me to do the things I am doing, the things I did in my Ph.D. or the things I want to accomplish, I would have stayed in Mexico," says Pablo Mendoza, president of the Mexican Talent Network–U.K. "If we could have the possibility to return to something that would have the potential that you see in other countries, many of us would come back."

The diaspora may indeed be the country's greatest asset. Every Mexican scientist I spoke to said he or she hoped to go home someday to support Mexican science. Dozens of expat associations, akin to Mendoza's, link Mexican researchers and entrepreneurs from New Zealand to Germany.

GREEN SHOOTS

TRUE TO MEXICO's schizophrenic nature, it is also producing an increasing number of success stories. According to the *New York Times,* in 2012 Mexico was among the largest exporters of IT services in the world, just behind India, the Philippines and China. People such as Blanca Treviño, CEO of the international IT firm Softtek, are convinced that Mexico is on the verge of a blossoming information economy.

In Mexico, research hubs—such as the biotech one in Cuernavaca and an automotive engineering one in Toluca—are partially directed by CONACYT (pronounced CONE-a-SEET), Mexico's primary science-funding arm (analogous to the U.S. National Science Foundation). Although some argue that government cannot dictate innovation, many CONACYT centers have overcome the start-up obstacles Montes de Oca and Reynaud faced. Indeed, whereas Mexico will likely have to rely on the U.S. for the next swine flu vaccine, the U.S. will soon be relying on Mexico for such medical products as scorpion and spider antivenom.

Mexico's future may come down to how successfully Peña Nieto is in his campaign to promote innovation. He has positioned himself as a kind of fresh, Silicon Valley leader. At the same time, however, he brought a party to power that ruled with a tight fist for more than 70 years, doling out CONACYT money for political favors—the antithesis of the meritocratic, entrepreneurial values of Silicon Valley.

But Peña Nieto is not the whole story. In greater numbers, Mexicans are breaking away from the government-as-a-guide model and striking out with new ideas. And increasingly they are whittling away the obstacles. Reynaud, for one, is not ready to give up. "Three and a half years that we operated at full scale, we made probably a million and a half pesos [around $115,000]," he says. "We were very close to getting out of the Valley of Death," referring to the gap between the laboratory and the market.

Would he do it again? "Yes," he says. "Yes, I would if I had the right idea. I've learned so much, and next time it will be different." Then he lets out a nervous laugh. SA

***Erik Vance** is a science writer based in Mexico City.*

MORE TO EXPLORE

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SCIENTIFIC AMERICAN ONLINE
For more on the state of the world's science, go to ScientificAmerican.com/oct2013/global-science

NEUROSCIENCE

The disorder remains a medical mystery with no cure in sight, but some existing therapies produce lasting benefits, and more are on the horizon

Help for the Child with Autism

By Nicholas Lange and Christopher J. McDougle

IN BRIEF

A deep-seated inability to interact with parents, siblings and other children can sometimes lead to a toddler's receiving a diagnosis of autism at about two years of age.

Help may come from early delivery of therapies that improve communication and social skills. Better skills can lay the groundwork for entering regular schools and pursuing relationships with friends and family.

Improved understanding of the biology of autism may permit development of new diagnostic techniques and a range of drugs to complement behavioral therapies aimed at enhancing social skills.

Photographs by Timothy Archibald

JAYDEN, playfully upended by his mother, Adrianna Hannon, received a diagnosis of autism at 22 months.

Nicholas Lange is associate professor of psychiatry and biostatistics and director of the Neurostatistics Laboratory at Harvard Medical School and McLean Hospital.

Christopher J. McDougle is director of the Lurie Center for Autism at Massachusetts General Hospital for Children, a multidisciplinary treatment facility.

WHEN ADRIANNA AND JERMAINE HANNON'S SECOND CHILD, JAYDEN, WAS 14 months old, the California couple began to worry that something was wrong. The child became preoccupied with toy cars, turning them over and rolling their wheels ceaselessly at an age when most other toddlers flit from one activity to another. Jayden would also line up cars, magazines or blocks on the floor or a table in as straight a line as he could make, never stacking objects as other kids would.

At 16 months, Jayden began to stop blurting the short phrases he had been using for four or five months—"Up, Mom," "Picky-up" and "Abby," his big sister's name—and he rarely looked toward family members when they called. One day around that same age, a large pot dropped by accident near to where Jayden was sitting, but the toddler did not respond at all. The pediatrician told Adrianna not to worry about Jayden's behavior, because child development tends to occur in bursts, especially in boys, and speech often develops later than in girls. At the pediatrician's request, Adrianna and Jermaine took their child to an audiologist to test his hearing, which turned out to be normal.

Jayden took another turn for the worse at 18 months when a high fever of 104 required a visit to the emergency room. A complete medical workup failed to locate the source of the fever, and the child returned home with his parents. The temperature eventually subsided, but Jayden never spoke another word. Neither did he respond when his name was called, and he made eye contact only with his mother.

This alarming series of events in Jayden's life still had not tapered off by 22 months. If he wanted something, he would grab Adrianna's or Jermaine's hand and bring them to the object he desired. He continued to be captivated by toy car wheels, rolling them without pause. He also was enthralled with a Mickey Mouse video on his iPad, which he would play over and over until asked to stop. Jayden loved, too, a program featuring the chugging Thomas the Tank Engine, with its crashing sound effects. The parents eventually decided to bring Jayden to a nearby early intervention clinic for children suspected of having autism, or, in clinical terminology, autism spectrum disorder—a condition marked, to varying degrees, by persistent deficits in communicating and interacting with others and a propensity to engage in repetitive behaviors, such as rocking or repeating sounds over and over.

Based on the careful observation of Jayden over the course of a few hours and on the wealth of details furnished by his parents, a psychologist at the clinic gave Adrianna and Jermaine the devastating news that their child did, indeed, have autism. Both parents initially wondered if they could have done something to cause the disorder. And, despite their suspicions, Adrianna recalls, Jermaine, an engineer, took a while to "get his head around" the clinic's confirmation of their fears. Having taught special education classes for 12 years, Adrianna took the diagnosis more in stride. She kept going by repeating to herself silently: "I can't quit," adding in another inspirational motto: "If I can't give him my all, then what can I expect anyone else to give him?"

Adrianna and Jermaine's experiences with Jayden resemble those of the thousands of parents whose children receive a diagnosis of autism spectrum disorder every year. As in Jayden's case, the condition remains a vexing enigma that taxes a physician's diagnostic powers. In the 70 years since psychiatrist Leo Kanner first coined the term "early infantile autism," scientists have yet to find any objective measurement—whether a molecule, a gene, electrical activity in a brain circuit or a consistent difference in brain size—to pinpoint how it originates.

Researchers are desperately trying to identify such biological clues in the hope that the information will facilitate diagnosis and the development of better treatments. To date, some drugs have shown that they can manage the irritability, mood swings and tantrums that afflict the child with autism. But nothing approved by the Food and Drug Administration deals with the basic symptoms: the language, social problems and repetitive gesturing.

The need is pressing. In the U.S. alone, about 800,000 people younger than 18 years are on record as having autism spectrum disorder, and the number continues to move upward. Some of the rise stems from increased screening: for nearly six years the American Academy of Pediatrics has recommended examining all children at 18 and 24 months of age for the telltale signs. The trend also results from a broadening of the complex diagnostic criteria for autism spectrum disorder. But even if those changes had not occurred, the numbers of families needing help would be large.

The seemingly bleak outlook is counterbalanced by a few

MOTHER AND CHILD play at the University of California, Davis, where three-year-old Jayden Hannon goes for treatment to improve his communication skills.

encouraging recent developments. In the past few years medical professionals have begun to spread the important message that a few nonpharmaceutical treatments can profoundly help children like Jayden. Begun early, therapies that ground the child with autism in appropriate forms of social behavior—such as looking at a mother's face as she speaks—may mean the difference between years in a special school or institution versus a normal track for the elementary and secondary years and the eventual hope of an adulthood with a job and family. In coming years, what is more, behavioral therapies may be supplemented by new technologies that will provide a definitive diagnosis before children reach their second birthday and by drugs that may correct biochemical imbalances underlying the disorder.

EARLY INTERVENTIONS BRING HOPE

WAITING ANOTHER DECADE for approval of a new drug is an agonizing prospect for the parents of a recently diagnosed child. Initial despair, however, can be tempered by the knowledge that a few good treatment options already exist. The latest research has shown that the brain of a toddler with autism can learn and change in response to behavioral therapies that enhance the child's social or language skills or that address another common problem: difficulties in engaging in play and other typical toddler activities. The flexibility demonstrated by the young child's brain opens new possibilities for intensive one-on-one therapy with trained professionals and parents to alleviate the difficulties with speech and social interactions that are a hallmark of the disorder.

One early intervention method derived from developmental psychology and applied behavior analysis (a technique for improving cognitive, language and social skills) is known as the Early Start Denver Model (ESDM). An ESDM therapist tries to deal with the difficulty a child with autism has in heeding social cues—facial expressions, gestures and spoken words. ESDM and other programs—such as Joint Attention, Symbolic Play, Engagement and Regulation—draw the attention of children to faces and voices. Healthy young children react more to a face than to a block, yet the pattern reverses for the child with autism, who typically responds more to an object than to a parent's gaze.

An ESDM therapist tries to encourage the child to focus attention. The professional will present a toy, perhaps name the toy in an inviting way and, when the child looks, will share it and start to play. The therapist tries to keep a child engaged in rounds of play intended to cultivate a nascent liking for social activities, all the while teaching social and communication skills.

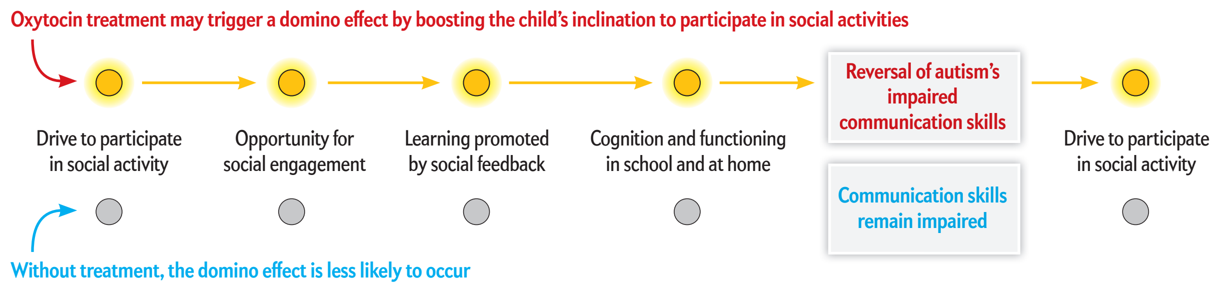
ESDM has now begun to receive validation from formal scientific studies. With funding from the National Institutes of Health, Geraldine Dawson of Duke University and Sally J. Rogers of the University of California, Davis, have evaluated the technique and have recently reported the strongest evidence to date of the effectiveness of an early intervention for autism.

After two years of intensive training beginning anywhere from 18 to 30 months of age, children paid attention more to faces than did youngsters with autism in non-ESDM behavioral programs. The children who received ESDM scored higher on cognitive tests: their developmental quotient (an IQ test for very young children) rose in the study by 10.6 points more on average than did that of children in non-ESDM behavioral programs. The severity of social deficits and repetitive behaviors diminished, although some symptoms not directly related to autism lingered.

Imaging shows that the brain undergoes desirable changes as well. Brain areas activated when a child looks at faces lit up more in children with autism who received ESDM relative to those in in non-ESDM programs. In fact, the brain response of the ESDM-trained youngsters was identical to that of typical four-year olds. When charting electrical brain activity with electroencephalography (EEG), the researchers noted an increase in power (the amount of energy in the signal) for certain types of

"Cuddle Chemical" Targeted as Autism Drug

Oxytocin's ability to promote interaction with others has generated interest in using it to treat autism's social deficits. In the child with autism, oxytocin could, in theory, increase the drive to form relationships and thereby lead to a virtuous cycle (*yellow*) that ultimately enhances cognitive functioning. An initial verdict on the chemical's effectiveness awaits the outcome of a clinical trial now under way.



brain waves known as theta oscillations in an area below the brain's surface called the hippocampus, so named from the Greek *hippokampos* because it resembles the shape of a seahorse. Increases in theta power correlate with more focused attention and short-term memory function.

Researchers also found a reduction in the power of alpha oscillations—which generate EEG recordings that cycle up and down more quickly than theta waves—in several regions, including the hippocampus. A lower level of alpha power hints that the brain was becoming more attuned to people's faces. Increased theta and decreased alpha together reflect higher levels of electrical activity at the surface of the brain, or cerebral cortex, and specifically in the prefrontal and anterior cingulate cortices that are involved in the perception of faces. Observing these changes, the researchers conjecture that ESDM may spur brain changes in the treated children that may explain their higher scores on cognitive tests.

ESDM brought about these changes after more than 2,000 hours of intensive therapy over the course of two years, a labor of two hours twice daily for five days a week. A drug that could replace or hasten this process would make a world of difference to children and their families. The latest research has started to target a range of medications that address symptoms, including impaired social communication, hyperactivity and inattention, as well as repetitive, ritualistic behaviors and sleep disturbances.

A leading prospect for a drug that could mimic the benefits of ESDM is the brain hormone oxytocin, which has made headlines in the popular science press variously as the "cuddle" chemical, the "moral molecule" and the "trust hormone." Known in the medical textbooks for its role in pregnancy, oxytocin readies a woman's body for childbirth. As levels rise, breasts swell and fill with milk, and later the hormone triggers labor. In the past 25 years researchers have learned that oxytocin, present in men as well, appears to play a role in promoting the bonding of infant to mother and cementing trust between friends. The hormone may even induce a sense of attachment to the baby in fathers-to-be.

Hope that oxytocin might help youngsters with autism comes from the observation that when the compound is administered in single doses either intravenously or within the nasal passages, the child with autism who normally fails to distinguish whether a new acquaintance is being "mean" or "nice" can suddenly detect the difference. Genetic studies add further evidence of oxytocin's role as a chemical that acts as a general social sensitizer and one that does so particularly in individuals with autism. Mice genetically tweaked to shut off the gene *CD38,* involved in making oxytocin, display less trust and recognition of other animals. Also, patients with autism have fewer oxytocin "receptors"—proteins that bind to oxytocin and convey its messages into specific nerve cells—and therefore lower levels of oxytocin.

These findings pave the way for larger studies. The NIH is now providing $12.6 million for five institutions to conduct a trial of intranasal oxytocin in which patients are randomly assigned to a treatment or control group. The Study of Oxytocin in Autism to Improve Reciprocal Social Behaviors (SOARS-B) should determine within a few years whether oxytocin becomes a routine part of treatment. Ascertaining whether the hormone is an effective drug is especially important because a large number of parents already administer oxytocin to their children with autism, using prescriptions from physicians allied with the DAN! (Defeat Autism Now!) faction. Yet the evidence so far is not conclusive enough to justify the practice. If oxytocin receives validation through this study, it might be recommended to facilitate ESDM by readying a child to respond to the ministrations of a therapist.

GENETIC CLUES

THE LONG ROAD TO A CURE—or at least better therapies—will require a more incisive understanding of what lies behind the mental and physical symptoms of autism. The genetic underpinnings, one important factor, remain largely a mystery because identifying the relevant mutations is a daunting task. Some studies suggest that an individual's predisposition is rooted in alterations in as many as 400 to 800 genes. This work finds that the disorder involves what are called copy number variants: the addition or deletion of large swathes of DNA potentially containing several genes.

Basic research into how autism develops is now trying to disentangle this complex genetic web. One of the most exciting recent findings came this past January. It hinted that the numb-

Graphic by Scientific American

ingly complex genetics of autism might be less convoluted than originally thought. The project examined the genetics of 55 patients from nine Utah families who collectively turned out to have 153 copy number variants that were not present in children without autism and 185 copy number variants associated with autism from the published literature. The geneticists searched for those same copy number variants in 1,544 children with autism from the Autism Genetic Resource Exchange (AGRE) and Children's Hospital of Philadelphia (CHOP) and in 5,762 control subjects, unrelated to one another or to the children in Utah. A stringent molecular checking procedure eventually narrowed down the total to 15 familial and 31 literature copy number variants that seemed most likely to be implicated in some fashion.

More analysis is needed to clarify how the variants might contribute to autism and to explain the contribution of other nongenetic autism triggers, such as hormonal imbalances in the womb and exposure to chemicals in the environment. But this important study—and its ability to eliminate from consideration many of the originally targeted copy number variants—provides evidence that a large number of genetic factors putatively linked to autism in the scientific literature might be ultimately ruled out.

Even with a winnowing process that reduces dramatically the number of suspect genetic elements, the possibility of finding a single autism gene that unlocks the underlying disease process in everyone will never materialize in the vast majority of cases. Most of the time at least a handful of genes are sure to be involved, each one potentially having a relatively minor role in precipitating symptoms. Many of these genes may contain so-called de novo mutations—ones that are present for the first time in the fertilized egg.

A few autism cases, however, have been shown to derive from a single disrupted gene and are proving vitally important in advancing research. Scientists are studying individuals with very rare single-gene mutations that account for about 5 percent of autism cases. Exploring the psychological and molecular disorders in these children should offer clues to what goes wrong in the more common cases where multiple genes are activated in a manner that induces the symptoms of autism.

Investigators have uncovered several of these disorders that result from single-gene mutations and lead to autism, along with sets of unrelated symptoms. One prominent example is Rett syndrome, which occurs mostly in girls and impairs development of brain circuits. It leaves children with IQs that are difficult to assess and, at times, a severe form of autism that leads to the loss of any rudimentary language and basic motor skills already acquired. Research has focused on compounds that can reverse these symptoms by nourishing stunted brain circuits, among them a hormone called IGF-1, or insulinlike growth factor 1. Investigators have shown that mice with a condition resembling Rett show fewer symptoms after dosing with a compound derived from IGF-1. A small trial of the IGF-1 derivative in as many as 50 children with autism has passed initial safety testing, and work is now beginning to assess its ability to reverse symptoms.

As research progresses, future studies must come to grips with the complexity of a disease with multiple causes, differing degrees of severity, and the involvement of large areas of the brain that regulate basic social behaviors and communication skills. A multipronged approach will be needed to develop ways to accurately detect the initial onset of symptoms in an 18-month-old toddler and to devise treatments that extend ultimately to correct the functioning of defective brain cells. Beyond an analysis of genetics, researchers looking for better diagnostic tools are turning to brain imaging. Studies have begun on techniques that image a few of the 40 percent of autism patients with minimal or no verbal ability in an attempt to find better criteria for diagnosing autism.

CELLULAR HELPERS

DOWN AT THE CELLULAR LEVEL, researchers are manipulating stem cells in laboratory dishes with the goal of developing new treatments. Stem cells have the ability to turn into any of several cell types. First, investigators convert specialized but easily accessible cells from a patient, usually from the skin, into stem cells known as induced pluripotent stem cells [see "Your Inner Healers," by Konrad Hochedlinger; Scientific American, May 2010]. Then they treat these cells in ways that convert them into brain cells, such as neurons or supporting cells known as glia. Or they can begin with stem cells from frozen and stored umbilical cord blood of a child with autism. Now the researchers have the equivalent of neurons or glia taken from the brain of a person with autism, replete with genetic anomalies.

An analysis of the particular genetic makeup—and which genes are active in the newly minted neurons—might assist in determining where a young child could be placed on the autism spectrum, whether he or she is afflicted with a mild form of the disorder or has a severe case that will prevent the uttering of even a single word. And if the cells respond well to a particular drug—forming better connections with other cells—researchers would have reason to hope that the person might respond favorably as well. By applying such techniques, doctors may one day be able to determine which medications would best help address particular symptoms.

The longer horizon holds even more far-reaching possibilities that are today only one step removed from the realm of a science-fiction story. Consider the possibility of a cell transformed into a neuron or glial cell in the laboratory that holds genetic material identical to that of the donor but has perhaps been genetically altered to correct some molecular defect involved in autism. In what is today a wholly theoretical scenario, a child with autism could be implanted with these stem cells and then exposed to therapeutic learning experiences, such as those provided by ESDM. This combination of genetic and behavioral therapies could then reshape the nervous system at the cellular and molecular levels and perhaps dramatically improve communication difficulties and repetitive behaviors. If such futuristic scenarios ever materialize, we may one day be able to say that we indeed are nearing a cure for children such as Adrianna and Jermaine's young Jayden. SA

MORE TO EXPLORE

Early Behavioral Intervention Is Associated with Normalized Brain Activity in Young Children with Autism. Geraldine Dawson et al. in *Journal of the American Academy of Child & Adolescent Psychiatry,* Vol. 51, No. 11 , pages 1150–1159; November 2012.

Learn the Signs. Act Early. Centers for Disease Control and Prevention: www.cdc.gov/ncbddd/actearly/index.html

SCIENTIFIC AMERICAN ONLINE
Watch a video of a child with autism undergoing therapy to help improve social communication skills at **ScientificAmerican.com/oct2013/autism**

THE DATA-DRIVEN SOCIETY

The digital traces we leave behind each day reveal more about us than we know. This could become a privacy nightmare—or it could be the foundation of a healthier, more prosperous world

By Alex "Sandy" Pentland


Just applied for a seventh credit card
Recent shift in text-messaging pattern; new girlfriend likely
Travels a mile out of way to work each day
According to cell-phone GPS data, walks 5.7 miles per day
Web and phone records suggest dissatisfaction with physician
BROADWAY LEGENDS
"Living your life in the public eye is a series of bad hairdos."
Rob Lowe
THE LION
PALACE
ELTON JOHN AND TIM RICE'S
1-800-Mattress
SPECTACOLOR.COM
TIMES SQUARE VISITORS CENTER
OPEN 24 HOURS

Alex "Sandy" Pentland directs the M.I.T. Human Dynamics Laboratory and co-leads the World Economic Forum's big data and personal data initiatives. His next book, *Social Physics*, will be published in January 2014 by Penguin Press.

BY THE MIDDLE OF THE 19TH CENTURY, RAPID URBAN GROWTH SPURRED BY THE INDUSTRIAL REVOLUTION HAD CREATED URGENT SOCIAL AND ENVIRONMENTAL PROBLEMS. CITIES RESPONDED BY BUILDING CENTRALIZED NETWORKS TO DELIVER CLEAN WATER, ENERGY AND SAFE FOOD;

to enable commerce, facilitate transportation and maintain order; and to provide access to health care and energy. Today these century-plus-old solutions are increasingly inadequate. Many of our cities are jammed with traffic. Our political institutions are deadlocked. In addition, we face a host of new challenges—most notably, feeding and housing a population set to grow by two billion people while simultaneously preventing the worst impacts of global warming.

Such uniquely 21st-century problems demand 21st-century thinking. Yet many economists and social scientists still think about social systems using Enlightenment-era concepts such as markets and classes—simplified models that reduce societal interactions to rules or algorithms while ignoring the behavior of individual human beings. We need to go deeper, to take into account the fine-grained details of societal interactions. The tool known as big data gives us the means to do that.

Digital technology enables us to study billions of individual exchanges in which people trade ideas, money, goods or gossip. My research laboratory at the Massachusetts Institute of Technology is using computers to look at mathematical patterns among those exchanges. We are already finding that we can begin to explain phenomena—financial crashes, political upsets, flu pandemics—that were previously mysterious. Data analytics can give us stable financial systems, functioning governments, efficient and affordable health care, and more. But first we need to fully appreciate the power of big data and build a framework for its proper use. The ability to track, predict and even control the behavior of individuals and groups of people is a classic example of Promethean fire: it can be used for good or ill.

THE PREDITIVE POWER OF DIGITAL BREAD CRUMBS

As we go about our daily lives, we leave behind virtual bread crumbs—digital records of the people we call, the places we go, the things we eat and the products we buy. These bread crumbs tell a more accurate story of our lives than anything we choose to reveal about ourselves. Our Facebook status updates and tweets deliver information we choose to tell people, edited according to the standards of the day. Digital bread crumbs, in contrast, record our behavior as it actually happened.

We are social animals, and our behavior is never as unique as

IN BRIEF

Today's cities and governments still operate according to principles developed two centuries ago, during the industrial revolution. To address 21st-century problems such as exploding population growth and climate change, we need new thinking.

Big data can deliver that thinking. The digital bread crumbs we leave behind as we go about our daily lives—which reveal more about us than anything we choose to disclose—provide a powerful tool for tackling social problems.

Yet concerns about misuse of this information are valid. Before data mining can deliver a healthier, more prosperous society, we need a New Deal on Data that gives individuals far more control over their information than they have today.

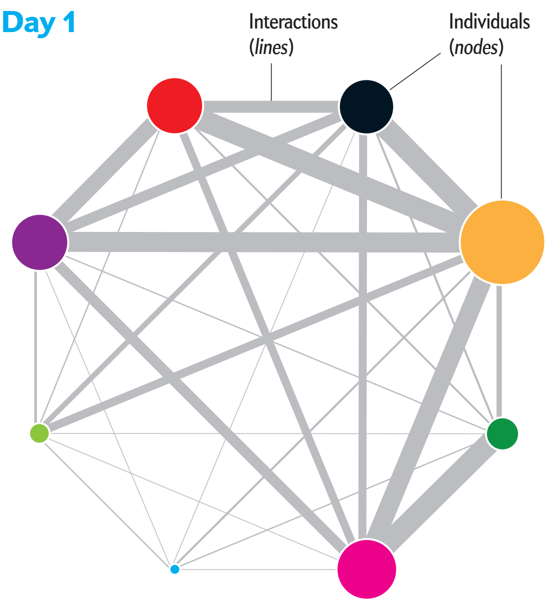
PRECEDING PAGES: ANDREW MOORE *Gallery Stock*

CASE STUDY

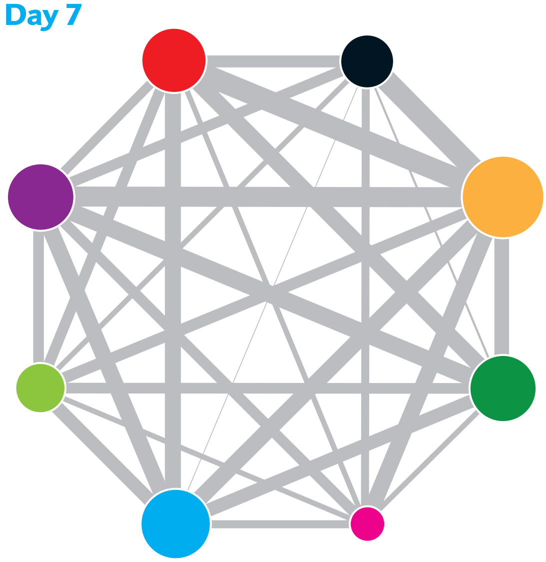
Group Dynamics

By tracking social interactions with sensor-equipped ID badges or cell-phone data, it is possible to make group dynamics visible, enabling team members to see how they work together. In the case depicted below, the author and his team tracked the dynamics of an eight-person brainstorming group and gave members a diagram of their interactions at the end of each day. The size of the circle surrounding each member represents the amount that person communicated with the group; the width of the lines connecting individuals represents the amount those two communicated with each other. By using the diagrams to diagnose weak links, the team became more interactive and, thus, more productive.

Day 1



Day 7



SOURCE: COURTESY OF SOCIOMETRICSOLUTIONS.COM

we might think. The people you call, text and spend time with—even the people you recognize around the neighborhood but have never formally met—are likely to be similar to you in all kinds of ways. My students and I can tell whether you are likely to get diabetes by examining the restaurants where you eat and the crowd you hang out with. We can use the same data to predict the sort of clothes you are inclined to buy or your propensity to pay back a loan. Because our behavior changes when we feel like we are getting sick—we go different places, buy different things, call different people and search for different terms on the Web—it is now possible, using data analytics, to make a constantly updatable map that predicts where residents of a city are most likely to come down with the flu at any given moment.

The mathematical patterns within big data that provide the most insight into the functioning of society involve the flow of ideas and information between people. We can see this flow by studying patterns of social interaction (face-to-face conversations, telephone calls, social-media messaging) and by assessing the amount of novelty and exploration in individuals' purchasing patterns (as seen in credit-card data) or movement patterns (as seen in GPS tracks). The flow of ideas is central to understanding society not only because timely information is critical to efficient systems but also because the spread and combination of ideas form the basis of innovation. Communities that are cut off from the rest of society risk becoming stagnant.

Among the most surprising findings that my students and I have discovered is that patterns of idea flow (measured by purchasing behavior, physical mobility or communications) are directly related to productivity growth and creative output. Individuals, organizations, cities, and even entire societies that engage with one another and explore outside their social group have higher productivity, greater creative output and even longer, healthier lives. We see variations on this pattern in all social species, even bees. Idea flow seems to be essential to the health of every society.

Consequently, when we analyze companies and governments, it is useful to think of them as idea machines. These machines harvest and spread ideas primarily through individual interactions. Two mathematical patterns provide evidence for healthy idea flow. The first is *engagement,* which we define as the proportion of possible person-to-person exchanges within a work group that regularly occur. The relationship between engagement and productivity is simple: high levels of engagement predict high group productivity, almost no matter what that group is working on or what kinds of personalities its members have. The second factor is *exploration*—a mathematical measure of the extent to which the members of a group bring in new ideas from outside. Exploration is a good predictor of both innovation and creative output.

In field experiments conducted at companies around the world, my students and I have measured levels of engagement and exploration by equipping employees with sociometric ID badges, electronic devices that track person-to-person interactions. We have found that increasing the amount of engagement within a group can dramatically improve productivity while simultaneously reducing stress. For instance, after learning that call centers usually schedule coffee breaks so that only one person has a break at any given time, I persuaded the manager of a Bank of America call center to schedule coffee breaks simultaneously. The goal was to promote more engagement between em-

Graphic by Scientific American

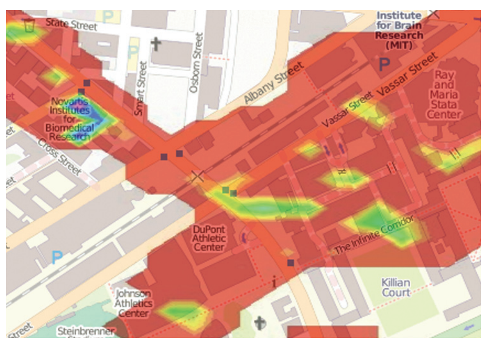
ployees. This single change resulted in a productivity increase of $15 million a year.

We have also found that exploration—establishing new connections among people—is an excellent predictor of innovation and creative output. Rich channels of communication, particularly face-to-face interaction, matter much more than electronic communication channels. In other words, e-mail can never fully replace meetings and conversations.

We have also found that an oscillating pattern of exploration and group engagement—in which people engage the group, then go find new information, bring it back, then repeat the process—is consistently associated with greater creative output. In established research organizations, my colleagues have been able to measure this pattern in face-to-face interactions and use these measurements to accurately identify researchers' top creative days. The same approach works with virtual teams, whose members are distributed across many locations.

Similar patterns of information flow predict the productive output of entire cities and regions. Patterns of community engagement and out-of-community exploration even predict social outcomes such as life expectancy, crime rate and infant mortality. Neighborhoods that are information ghettos do as poorly as physical ghettos do, whereas neighborhoods that are engaged with one another and connected to surrounding communities tend to be more healthy and prosperous.

For the first time in history, we can see enough about ourselves to build social systems that work better than the ones we have always had.



HOT ZONES: By mining cell-phone data, researchers can map the places where people are most likely to catch the flu. Above, an example from an experiment on the M.I.T. campus.

COURTESY OF WEN DONG AND ALEX PENTLAND

MAXIMIZING IDEA FLOW

USING BIG DATA to diagnose problems and predict successes is one thing. What is even more exciting is that we can use big data to *design* organizations, cities and governments that work better than the ones we have today.

The potential is easiest to see within corporations. By measuring idea flow, it is usually possible to find simple changes that improve productivity and creative output. For instance, the advertising department of a German bank had experienced serious problems launching successful new product campaigns, and they wanted to know what they were doing wrong. When we studied the problem with sociometric ID badges, we found that while groups within the organization were exchanging lots of e-mails, almost no one talked to the employees in customer service. The reason was simple: customer service was on another floor. This configuration caused huge problems. Inevitably, the advertising department would end up designing ad campaigns that customer service was unable to support. When management saw the diagram we produced depicting this broken flow of information, they immediately realized they should move customer service to the same floor as the rest of the groups. Problem solved.

Increasing engagement is not a magic bullet. In fact, increasing engagement without increasing exploration can cause problems. For instance, when postdoctoral student Yaniv Altshuler and I measured information flow within the eToro social network of financial traders, we found that at a certain point people become so interconnected that the flow of ideas is dominated by feedback loops. Sure, everyone is trading ideas—but they are the same ideas over and over. As a result, the traders work in an echo chamber. And when feedback loops dominate within a group of traders, financial bubbles happen. This is exactly how otherwise intelligent people all became convinced that Pets.com was the stock of the century.

Fortunately, we have found that we can manage the flow of ideas between people by providing small incentives, or nudges, to individuals. Some incentives can nudge isolated people to engage more with others; still others can encourage people mired in groupthink to explore outside their current contacts. In an experiment with 2.7 million small-time, individual eToro investors, we "tuned" the network by giving traders discount coupons that encouraged them to explore the ideas of a more diverse set of other traders. As a result, the entire network remained in the healthy wisdom-of-the-crowd region. What was more remarkable is that although we applied the nudges only to a small number of traders, we were able to increase the profitability of *all* social traders by more than 6 percent.

Designing idea flows can also help solve the tragedy of the commons, in which a few people behave in such a way that everyone suffers, yet the cost to any one person is so small there is little motivation to fix the problem. An excellent example can be found in the health insurance industry. People who fail to take medicine they need, or exercise, or eat sensibly have higher

health care costs, driving up the price of health insurance for everyone. Another example is when tax collection is too centralized: local authorities have little incentive to ensure that everyone pays taxes, and as a result, tax cheating becomes common.

The usual solution is to find the offenders and offer incentives or levy penalties designed to get them to behave better. This approach is expensive and rarely works. Yet graduate student Ankur Mani and I have shown that promoting increased engagement between people can minimize these situations. The key is to provide small cash incentives to those who have the most interaction with the offenders, rewarding *them* rather than the offender for improved behavior. In real-world situations—with initiatives to encourage healthy behavior, for example, or to prompt people to save energy—we have found that this social-pressure-based approach is up to four times as efficient as traditional methods.

This same approach can be used for social mobilization—in emergencies, say, or any time a special, coordinated effort is needed to achieve some common goal. In 2009, for example, the Defense Advanced Research Projects Agency designed an experiment to celebrate the 40th anniversary of the Internet. The idea was to show how social media and the Internet could enable emergency mobilization across the U.S. DARPA offered a $40,000 prize for the team that could most quickly find 10 red balloons placed across the continental U.S. Some 4,000 teams signed up for the contest, and almost all took the simplest approach—offering a reward to anyone who reported seeing a balloon. My research group took a different tack. We split the reward money among those who used their social networks to recruit a person who later saw a balloon and those who saw a balloon themselves. This scheme, which is conceptually the same as the social-pressure approach to solving tragedies of the commons, encouraged people to use their social networks as much as possible. We won the contest by locating all 10 balloons in only nine hours.

A NEW DEAL ON DATA

TO ACHIEVE a data-driven society, we need what I have called the New Deal on Data—workable guarantees that the data needed for public goods are readily available while at the same time protecting the citizenry. The key to the New Deal is to treat personal data as an asset; individuals would have ownership rights in data that are about them. What does it mean to "own" your own data? In 2007 I suggested an analogy with the English common law tenets of possession, use and disposal:

You have the right to possess data about you. Regardless of what entity collects the data, the data belong to you, and you can access the data at any time. Data collectors thus play a role akin to a bank, managing the data on behalf of their "customers."

You have the right to full control over the use of your data. The terms of use must be opt-in and clearly explained in plain language. If you are not happy with the way a company uses your data, you can remove those data, just as you would close your account with a bank that is not providing satisfactory service.

You have the right to dispose of or distribute your data. You have the option to have data about you destroyed or redeployed.

At the World Economic Forum over the past five years, I have helped curate a discussion of these basic tenets among politicians, CEOs of multinational corporations, and public advocacy groups in the U.S., the European Union and around the world. As a result, regulations in the U.S., the E.U. and elsewhere (such as the new U.S. Consumer Privacy Bill of Rights) are already giving individuals greater control over their data while also encouraging increased transparency and insight in both the public and private spheres.

LIVING LABS

FOR THE FIRST TIME in history, we can see enough about ourselves to build social systems that work better than the ones we have always had. Big data promises to lead to a transition on par with the invention of writing or the Internet.

Of course, moving to a data-driven society will be a challenge. In a world of unlimited data, even the scientific method as we typically use it no longer works: there are so many potential connections that our standard statistical tools often generate nonsense results. The standard scientific approach gives us good results when the hypothesis is clear and the data are designed to answer the question. But in the messy complexity of large-scale social systems, there are often thousands of reasonable hypotheses; it is impossible to tune the data to all of them at once. So in this new era, we will need to manage our society in a new way. We have to begin testing connections in the real world far earlier and more frequently than we ever have before. We need to construct "living labs" in which we can test our ideas for building data-driven societies.

One example of a living lab is the open-data city we just launched in Trento, Italy, with cooperation from the city government, Telecom Italia, Telefónica, the research university Fondazione Bruno Kessler and the Institute for Data Driven Design. The goal of this project is to promote greater idea flow within Trento. Software tools such as our openPDS (Personal Data Store) system, which implements the New Deal on Data, makes it safe for individuals to share personal data (such as health details or facts about their children) by controlling where their information goes and what is done with it. For example, one openPDS application encourages the sharing of best practices among families with young children. How do other families spend their money? How much do they get out and socialize? Which preschools or doctors do people stay with for the longest time? Once the individual gives permission, such data can be collected, anonymized and shared with other young families via openPDS safely and automatically.

We believe that experiments like the one we are carrying out in Trento will show that the potential rewards of a data-driven society are worth the effort—and the risk. Imagine: we could predict and mitigate financial crashes, detect and prevent infectious disease, use our natural resources wisely and encourage creativity to flourish. This fantasy could quickly become a reality—our reality, if we navigate the pitfalls carefully. SA

MORE TO EXPLORE

Society's Nervous System: Building Effective Government, Energy, and Public Health Systems. A. Pentland in *Computer,* Vol. 45, No. 1, pages 31–38; January 2012.

Personal Data: The Emergence of a New Asset Class. World Economic Forum, January 2012. www.weforum.org/reports/personal-data-emergence-new-asset-class

The New Science of Building Great Teams. Alex "Sandy" Pentland in *Harvard Business Review;* April 2012.

SCIENTIFIC AMERICAN ONLINE
Watch a video interview with Pentland at ScientificAmerican.com/oct2013/pentland

Smart, strong and flexible, the octopus is an enticing model for an entirely new kind of many-armed, multitalented robot

By Katherine Harmon Courage

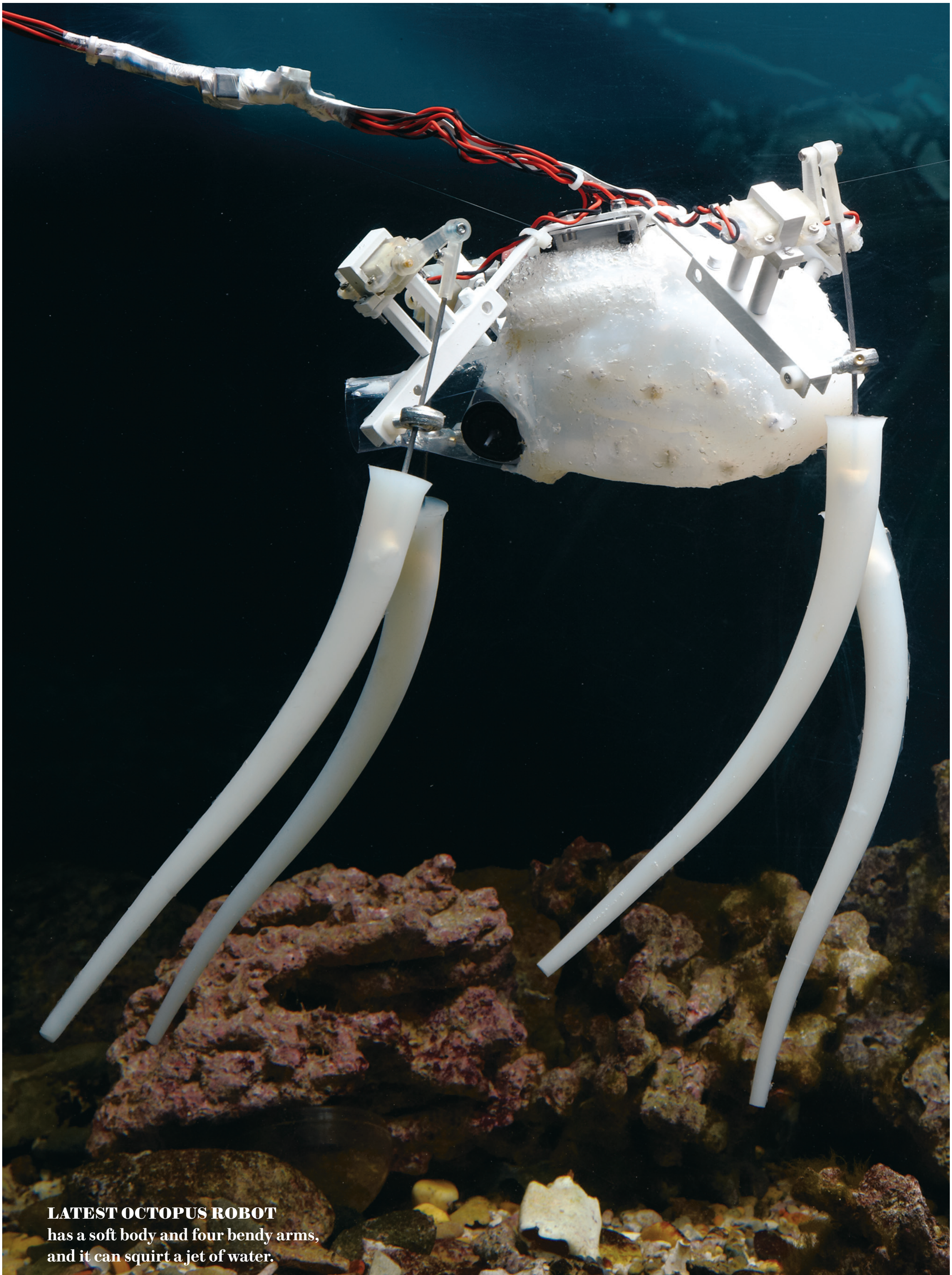
ROBOTICS

HOW TO BUILD A ROBOT OCTOPUS

OCTOPUSES ARE SOME OF THE MOST COMPLEX, BIZARRE AND INTELLIGENT CREATURES IN the sea. They can squeeze through holes smaller than a quarter, pull with hundreds of pounds of force, change the color and texture of their skin in an instant and, with their walnut-sized brains, figure out how to open a childproof pill bottle to reach a tasty morsel of crab. With such an impressive array of skills, it was only a matter of time before engineers started asking: Could we make a robot that behaves like an octopus?

The OCTOPUS Integrating Project is one group that is trying to answer just this question. This multi-institution, international collaboration is working toward a fully autonomous robotic octopus that could, like a real mollusk, accomplish feats that no hard-jointed bot ever could.

Cecilia Laschi, a biorobotics researcher at the Sant'Anna School of Advanced Studies in Pisa, Italy, has been coordinating the effort. She and her colleagues completed a prototype disembodied octopus arm in 2010 and are now building the remainder of the body—from mantle top to arm tip. Their goal is to create a robot that will move like an



LATEST OCTOPUS ROBOT
has a soft body and four bendy arms, and it can squirt a jet of water.

Photographs by Reinhard Hunger

octopus underwater and maneuver into tight spaces. It could be invaluable for search and rescue and exploration. But perhaps the most exciting aim of the project is to prove that creating an entirely soft-bodied robot is possible.

I visited Laschi and her colleagues at their laboratory in Livorno, a short train ride outside of Pisa. One of Laschi's researchers, biorobotics Ph.D. Laura Margheri, led me into the small, seaside facility. Inside, the many side doors were flung open, letting in a gentle Ligurian breeze and a view of boats in the harbor. At rows of workstations, some graduate students and postdocs labored away at their computers and tinkered with prototypes. In the center, at the head of the lab, was a large, well-appointed saltwater tank complete with rocks, starfish and one aging—but active—octopus. This mascot goes by the name of Andreino (an homage to a former colleague who caught him).

Margheri has been testing the octopus's natural abilities in hopes of mimicking them in the robots. She has rigged some clever experiments to see just how far octopuses can stretch their muscular hydrostat arms. In one exercise, an octopus uses a long arm to retrieve a treat from inside a long tube—something it can learn to do in just five training sessions over a couple of days. Margheri then places the food even farther down the tube and measures just how much these tonguelike arms can stretch. The arms, it turns out, can extend to about double their original length—an engineering challenge indeed.

The project leader's own background is in more traditional robotics. "I'm used to robots that have rigid links," Laschi explained. After working with neuroscientists and learning more about our own brains and how we coordinate our bodies, she started to feel a little frustrated by the traditional rigidity of classic robots and the absence of structures like muscles. So she and some more bio-oriented collaborators started to plan a daring soft-bodied robot project. And what better model than the octopus? "All biological systems have some soft material," she said, "but the octopus is very special because it has *only* soft material" (except for the beak, of course). "So we took it as the extreme—if you study this end of the spectrum, you can solve the others." A group at Harvard University has developed a four-legged octopus-inspired robot that can inch along on land and even (slowly) color camouflage. But it still requires tethers to air and liquid pumps and external controls to guide it.

To mimic the octopus more completely—from the inside out—Laschi's team used ultrasound technology to get a rare internal view of the octopus's arm and all its muscles at work. This perspective helped to clarify "the secret of the movement of the octopus arm," chimed in Matteo Cianchetti, another biroboticist in Laschi's lab. In the absence of a skeleton, three groups of muscles give the octopus arm its flexibility and structure, allowing it to change direction, length and even stiffness. To replicate the muscles, the researchers are using cables and springs forged from shape-memory alloys that bend when heated by an electric current and subsequently return to their original shape.

Although the muscles themselves can extend far beyond their typical length, the central nerve cord in each arm cannot. Instead each nerve bundle is folded in a zigzag configuration, somewhat like an accordion, so it can unfold as the arm extends. Taking a cue from living octopuses, Margheri and her team are packing processing wires into the center of the arm in a wavelike pattern.

Cianchetti showed me one of the silicone-skinned prototypes, which has a ghostly gray hue. By pulling on a few wires, he made it curl up into a spiral. I stuck my finger out, and the disembodied arm firmly wrapped its rubbery skin around my own with a disconcerting ease. By virtue of the arm's shape, proportions and the "musculature" inside, it naturally winds around whatever it is grasping. "It automatically adapts to that shape," Cianchetti said. Great, I thought with a shiver.

The researchers are studding the robot arm with sensors that integrate tactile perception and hope to also add some kind of suckerlike appendages. These might not, however, behave exactly like a living octopus's suckers, which are strong but also versatile—able to rotate, fold and even taste the environment around them. Other groups, including Frank Grasso's lab at Brooklyn College, are developing more refined robotic suction cups. And the U.S. Army Research Laboratory, in collaboration with other scientists, is already 3-D printing superstrong, individually activated suckers.

Scientists working on robot octopuses choose their materials carefully, so the robots can perform well underwater for long periods without corroding. The silicone that the OCTOPUS Integrating Project team is using has almost the same density as water, so it is buoyant—just like a real octopus.

Because an underwater robot, no matter how impressive, is only really functional if it can get around, some of the lab members are investigating various forms of locomotion. Marcello Calisti, another bioroboticist, is tackling the walking problem. Most real octopuses walk more with their back arms while feeling around with their front ones. But for the artificial version, the roboticists might instead have it reach out with its front arms, attach some suckers, then pull, a strategy that will also help with exploration and determining directional movement.

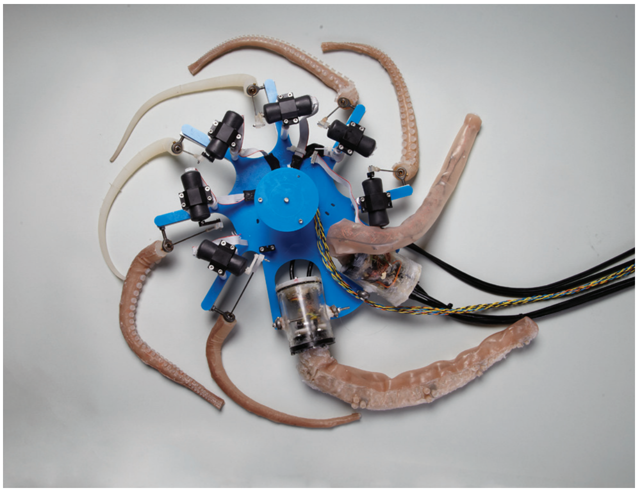
Calisti's workstation was next to a half-full inflatable kiddie pool used to test underwater crawling and other tasks. Calisti showed me his current prototype, made out of hard-material motors and fixed cables, which had only six arms and still looked rather primitive. But there was something eerie about it when Calisti played back a video of it in action crawling along, spiderlike. "It's a little bit creepy," he admitted. So far they have been able to program it externally, turn it loose in the pool, and watch it locate and retrieve objects. But the goal is to eventually put

IN BRIEF

The octopus has impressive brain and brawn. The smartest invertebrate on the planet, it is also a master of camouflage and contortion, squeezing its soft but muscular body into tiny spaces and swiftly transforming the color and texture of its skin to evade predators.

In recent years engineers have been trying to mimic the octopus's many talents in the form of a soft-bodied robot capable of technical feats no current terrestrial robot can accomplish.

Researchers have already devised a four-legged "octobot" that can crawl and change color, as well as eerily lifelike artificial octopus arms that curl around whatever they touch. Such robots will also help scientists better understand how living octopuses behave in their natural habitat.



OCTOBOT prototype featured a variety of arms.

the command center inside of it (and give it the full eight legs and a totally soft body).

Crawling, of course, is not the octopus's only means of getting around. In the real world, octopuses opt for jet-powered swimming when they need to make a quick escape. At the other end of the lab, Francesco Giorgio Serchi was trying to re-create the octopus's propulsion system in silicone. The water jet that octopuses can propel themselves with creates a swirl of water known as a vortex ring. The real animal generates this force by using its mantle muscles to suck up and squirt out water through its funnel.

Scientists are only now figuring out the fluid dynamics of the vortex ring, which squid and a few other underwater animals also employ. The goal is to mimic this feat of biophysics to someday propel small submarines or autonomous vehicles, Giorgio Serchi noted. As he pointed out, adapting this aquatic locomotion for our purposes would be a big step forward. With current technology, most "every kind of propulsion in the water environment is continuous," he said. Propellers and even water jet boats generate a constant motion. In contrast, octopus-inspired propulsion "would be the first example where you actually use a discontinuous jet." And not just for novelty's sake. "It's interesting," he remarked, "because it appears that it is especially efficient." Re-creating a vortex ring could give underwater vehicles extremely efficient acceleration.

But you can't just tie on a big turkey baster, fill it with water and squeeze. The octopus's system is a bit more nuanced and finely tuned than that. "Certainly the most complex aspect here is reproducing this capability of his to just contract a little bit, the width of the mantle, and change significantly the volume inside, which gets displaced," Giorgio Serchi said. "It's a challenge."

The octopus, however, is doing this with ease. So Giorgio Serchi decided not to reinvent the proverbial wheel. Instead he took a cast of a real octopus mantle and then reconstructed it in silicone. He showed me the detailed model. There were even cavities where the organs go, which, for now, he had filled with electronic components. "It's a big approximation," he conceded. But the results should also help inform biologists about how these cephalopods swim.

The next step for the roboticists is adding flexible intelligence to their creation. Aside from the engineering challenges, Laschi and the rest of the OCTOPUS Integrating Project researchers are vexed with a biological question, "How can an animal with a relatively small brain control such a huge amount of physical freedom and sensory data?" The jury is still out on how the animals do it, but that is not going to stop the engineers. So Laschi has two words: embodied intelligence. This means that each part of the body—octopus or robot—is, at least in part, in control of itself.

To run all those arms so exquisitely, "there *must* be a lot of embodied intelligence," she said. "Each arm has many neurons and controls a good part of the movements, but we don't have a real model from neuroscience of how it works."

Not only does neuroscience fail to explain these abilities, but traditional robotics also comes up short. Robotic control has been based on rigid, finite movements. But what do you do when you have a near infinite range of motion with multiple parts? This is, of course, precisely the dilemma that biologists have been coming up against as well when looking at the octopus itself.

In searching for solutions, Laschi and her team have turned to a common evolutionary answer: learning. Just as we and many animals—including cephalopods—learn at a young age how to control our limbs, so, too, will these soft-bodied robots. This approach is appealing, in part, because it does not require exhaustive modeling. Over time the robot octopus could learn to apply a single movement to many different tasks and to combine various movements for more complex challenges. If it encounters an obstacle—a rock on the seafloor, for example—it might run through a variety and combination of different known commands. Once it finds the movement or combination of movements that allow it to surmount the rock, it will remember to use the same techniques when faced with a similar roadblock. In this sense, it should learn somewhat as we do and eventually become more "intelligent."

To create an intelligent robot, the team first needs to engineer body feedback systems, including adding more sensors in the arms to detect how much the limbs have extended or contracted. The scientists might be able to use the shape-memory alloy spring itself as a sensor. "We will have both tactile sensors and some kind of position sensors," Laschi said.

Engineers have a long way to go in their quest to transform the amazing octopus into a robot. In the years to come, their achievements and failures alike will provide new insights into the biology of one of the ocean's craftiest creatures, as well as help robotics surpass the limitations of rigid structures to embrace smarter and far more flexible forms. SA

Katherine Harmon Courage is a Scientific American *contributing editor.* Octopus!, *which will be published in October, is her first book.*

MORE TO EXPLORE

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An Octopus-Bioinspired Solution to Movement and Manipulation for Soft Robots. M. Calisti et al. in *Bioinspiration & Biomimetics,* Vol. 6, No. 3; September 2011. http://iopscience.iop.org/1748-3190/6/3/036002

SCIENTIFIC AMERICAN ONLINE
To watch videos showing the latest octopus robot and highlighting amazing facts about octopuses, visit ScientificAmerican.com/oct2013/octopus-robot

ENERGY

RUSSIA'S NEW EMPIRE:

Nuclear Po

The federation is aggressively selling reactors all over the world, raising

By Eve Conant

EXPORT: Russia's new VVER reactors, under construction in Novovoronezh, are being ordered worldwide.

wer

safety concerns

FOR ANY COUNTRY THAT MAY be considering acquiring its first nuclear reactor, Russia's annual ATOMEXPO offers a seemingly simple solution. At a recent event, thousands of people from around the world flocked to a giant, czarist-era exhibition hall. A visitor could hear vendors such as Rolls-Royce talk about steam generators, watch reporters interview experts for a Russian nuclear-themed television program or pick up a "Miss Atom" calendar featuring the year's prettiest Russian nuclear workers.

The real action, though, was at a multilevel booth for Rosatom, Russia's state-owned nuclear company, which exuded a Steve Jobs vibe of pure whiteness and know-how. That was where "newcomers," as the Russians fondly call them, from nations that do not have nuclear power plants heard about options and signed cooperation agreements for Rosatom to build or even operate reactors for them. At one point, photographers snapped shots of Nigerian nuclear officials as they clinked champagne flutes with Rosatom chief Sergey Kirienko, celebrating their baby steps toward joining Russia's growing roster of clients, including Turkey and Vietnam. Rosatom has already finished reactors in China and India. In July, Finland chose the company over French and Japanese competitors for its next reactor.

The big show was all part of a Kremlin-backed $55-billion plan to make Russia a leading global supplier of nuclear power. Already the country intends to build roughly 40 new reactors at home, and it expects as many as 80 orders from other countries by 2030. Included are facilities that would generate power and desalinate water, of particular interest in the Middle East. The expansion comes as Germany is abandoning nuclear power, the U.S. industry is struggling and Japan is in the midst of soul-searching about its post-Fukushima intentions. President Vladimir Putin has called the build-out "a rebirth, a renaissance" of Russia's nuclear technology.

Rosatom is eyeing British and American markets, too—it owns uranium mines in Wyoming and supplies about half of the fuel used in U.S. reactors, according to the World Nuclear Association. But for now it is primarily targeting developing nations and countries that had close ties to the former Soviet Union. For some of these newcomers, Rosatom has a unique offer: it can be a one-stop nuclear shop. It will provide fuel and will permanently take back the spent fuel from its reactors—eliminating the need for some countries to build geologic waste repositories. That service, offered by no other country, "is a tremendous marketing advantage for the Russians," says Alan Hanson, who recently joined the Massachusetts Institute of Technology after 27 years as an executive at Areva, Rosatom's French competitor.

Russia is sweetening the deal by providing scholarships to young men

IN BRIEF

Russia is preparing to sell unconventional reactors to developing countries that have little nuclear power experience.

The models include breeder reactors that make plutonium, mini reactors meant to float on the ocean and pressurized-water reactors equipped with passive safety features intended to stop a reactor meltdown without human intervention.

Western experts say some of the models may not be as safe as Russian officials maintain and could increase the chance that weapons-grade material would spread worldwide.

Eve Conant, a freelance writer based in Washington, D.C., and a former staff writer and Moscow correspondent for *Newsweek,* traveled to Russia on a grant from the Pulitzer Center on Crisis Reporting.

and women from client nations to study in Russia and obtain degrees in "nuclear power plants and facilities." And because an average reactor costs at least $3 billion, Russia is offering the first ever rent-a-reactor program in which Rosatom builds and runs reactors on foreign soil.

Many of the world's nuclear experts are concerned that Russia is galloping ahead too fast. They worry that Rosatom is willing to do business with any nation, which could lead to the proliferation of nuclear material or know-how. Rosatom has had discussions with countries that the West considers dictatorships, such as Myanmar (Burma) and Belarus. And just this past July the president of Iran—a country mired in fresh U.S. sanctions over its nuclear ambitions—visited the Kremlin to ask Putin for more reactors beyond the one Russia already built.

Russian officials balk at the criticism and are enthusiastically casting a wide net. Kirill Komarov, a Rosatom executive tasked with overseas expansion, told reporters at a press conference in June 2012, "There is no country in which we will not be interested to build a plant."

Experts also worry that Russia's nuclear leaders do not place a top priority on safety. Although safety features are prominent in new designs, "the government owns and funds both the designer and the independent safety review. It was this arrangement in Japan that has been recently flagged as contributing to issues in the Fukushima accident," says Susan Voss, president of the Santa Fe consulting firm Global Nuclear Network Analysis and formerly a scientist working on reactor design at Los Alamos National Laboratory.

Rosatom spokesman Sergey Novikov insists that the federal supervisor, Rostechnadzor, "is absolutely independent." Russia says that all the reactor technologies Rosatom is promoting have the most modern safety features. But some Western experts remain dubious about how protective those features truly are.

FAST AND FURIOUS

RUSSIA IS ALREADY the world leader in developing one controversial option: fast-breeder reactors. More typical reactors in use worldwide consume enriched uranium fuel and generate waste that remains highly radioactive for thousands of years. Breeder reactors essentially recycle fuel. As the enriched uranium burns in the core, it generates neutrons, which collide with low-grade uranium (that cannot function as a fuel) in a blanket around that core, turning the uranium into, or "breeding," plutonium. The reactor can later consume that plutonium (it still generates highly radioactive waste). Breeder reactors can produce 10 to 100 times more energy from a set amount of uranium than the more standard varieties—boiling-water and pressurized-water reactors—can.

The U.S. built experimental breeder technology in the 1970s and 1980s but abandoned it—in part because abundant uranium supplies were cheap but also because the design heightens the chance for proliferation of weapons-grade uranium and plutonium. It "can provide cover for a weapons program," says Frank N. von Hippel, a physicist at Princeton University and former assistant director for national security at the White House Office of Science and Technology Policy. Voss adds that fast reactors give a country "a direct source of weapons-usable plutonium."

What is more, accidents can be very difficult to handle because the core is immersed in liquid-sodium coolant, in contrast to the water used to keep more standard reactors from overheating. Workers cannot just pop the lid to get to troubled areas because "sodium catches fire if exposed to air or water. And we live in a world of air and water," von Hippel explains. The Russians struggled through several fires to learn how to better control the technology, but von Hippel says another safety issue looms: a meltdown could lead to a small explosion that could "blow the top off a reactor" and widely disperse radioactive products such as plutonium, uranium, cesium and iodine.

Today the Russian BN-600, housed near Yekaterinburg, is the world's only commercially operating breeder reactor. Its workers are immensely proud that it has been operating for 30 years, 10 years longer than expected.

A Rosatom subsidiary, OKBM Afrikantov, has designed a BN-800 facility, now being built, and a BN-1200; the numbers in the reactor names give the power capacity, in megawatts (1,000 MW is a large reactor). The BN-800 can be modified to run on plutonium from retired nuclear weapons. A U.S.-Russia nonproliferation agreement stipulates that the BN-800 will be used to consume some of the stockpiles of Russia's weapons-grade plutonium. The BN-1200, however, is designed to produce plutonium for fuel, according to Leonid Bolshov, director of the Nuclear Safety Institute at the Russian Academy of Sciences.

Despite international hand-wringing, Rosatom has a long-term Advanced Nuclear Technologies Federal Program that envisions shifting a significant portion of its resources to breeder reactors by about 2050. The goal is a nuclear industry where all fuel is reprocessed, not dumped in unpopular storage sites. "We will have a closed fuel cycle; we have to," says Vladimir Galushkin, a passionate international coordinator at OKBM Afrikantov. "There is no other path."

FLOATING NUKES

THE SECOND controversial technology Russia is pursuing is the small modular reactor. It is a scaled-down version of the classic pressurized-water reactor. The small Russian models include spin-offs from old Soviet nuclear-powered submarines and icebreakers. They are much cheaper than the typical mammoth reactor, and they can be prefabricated to arrive at remote locations that might lack strong construction standards or a trained workforce. The drawbacks: they produce only 300 to 500 MW, and critics contend that mass production would scatter reactor risks more widely. Still, one Russian specialist, Dmitri Statzura, told me at a wind-whipped nuclear construction site in southern Russia that "mass production is a real possibility." He was particularly excited about the VBER, a 300-MW model that will first be built for remote areas of Kazakhstan.

At the same time, Russia is trying to shoehorn its breeder-reactor technology into a mini reactor called BREST. The de-

sign uses molten lead as the coolant, which is much less reactive to air and water than sodium is. Of course, lead is a known toxic substance, "but most industries know how to deal with it," says Kevan Weaver, director of technology development at TerraPower in Bellevue, Wash., which is developing its own fast mini reactors. "The Russians do have the most experience," Weaver explains. They have used their reactors in at least seven submarines and have built two onshore prototypes. TerraPower tests its prototypes in a Russian facility in Dimitrovgrad.

The potential spread of many fast small reactors worries groups such as Bellona, an international environmental organization in Oslo that tracks the Russian nuclear industry. Russia has arrested and jailed nuclear whistle-blowers, including one of Bellona's contributors, a Russian ex-navy officer accused of treason. Bellona has detailed nuclear accidents on Soviet submarines and says that four subs are lying dead on the ocean floor, their reactors still presenting a hazard.

What concerns Bellona environmental researcher Igor Kudrik lately, however, is Russia's desire to mass-produce mini reactors that can float. The country's first floating plant, the *Akademik Lomonosov,* is partially built and is scheduled to begin operating in 2016. The idea is to have easily maneuverable 35-MW reactors that could be towed to difficult-to-access regions or energy-intensive ventures such as desalination plants, with cables running to land to distribute power.

The U.S. toyed with the idea in the 1970s but considered it too dangerous, with a high potential for contaminating entire marine food chains. "I also can't imagine that floating nuclear reactors don't pose particular security risks when it comes to terrorists," says Sharon Squassoni, director of the Proliferation Prevention Program at the Center for Strategic and International Studies in Washington, D.C. Kudrik adds that remote locations would not have the people or gear needed to handle an accident or an incoming tsunami: "This is not a diesel generator that you can fix on your knee and restart." Nevertheless, China, Algeria, Indonesia, Namibia and others have expressed interest.

Bolshov downplays the concerns. He notes that the plants would be placed at the shoreline. "I do not see any difference between an at-shore and onshore plant" from a security standpoint, Bolshov says. In addition to boosting exports, the floating reactors could help Russia dominate the exploitation of the Arctic's offshore petroleum reserves as climate change makes more regions accessible for drilling.

A SAFER OPTION

ALTHOUGH RUSSIA is promoting its exotic breeders and floating mini nukes, it is most aggressively hawking its latest generation of pressurized-water reactors, known as VVERs. The infamous reactors that melted down in Chernobyl in 1986 also relied on pressurized water to make steam, which turns a turbine to create electricity. But VVERs have a fundamentally different design and are housed in a containment building; the Soviet Union did not build such structures around the Chernobyl reactors because they were huge.

Whether Russian training of foreign nuclear workers raises concerns or not, it is vital to preventing reactor accidents.

VVERs differ from those old models and from Western designs in several ways. For instance, they have horizontal steam generators, which Western experts agree are more accessible for maintenance. Russian fuel pellets also have holes in their centers, which provide better cooling for safety, according to Vladimir Artisyuk, vice rector for science and foreign affairs at the Central Institute for Continuing Education and Training in Obninsk. The biggest advances are passive safety features—systems intended to shut a reactor down without human intervention, even if the plant loses backup electricity from the outside power grid. Among the features are water tanks that can flood the core using just gravity. The reactor can also be cooled with air. "In Fukushima, this one system would have saved them," chief engineer Viktor Vagner claims proudly at the site of two reactors under construction near Russia's southern border.

Rosatom's passive safety systems have already been built into India's Kudankulam reactors, and they are making the VVER a popular choice. Rosatom is building, or has signed contracts for, 19 VVERs outside of Russia. New Western designs, such as Westinghouse's AP1000 pressurized-water reactor, include similar features, and most experts interviewed for this story say they do not see any significant differences in safety between the Western and Russian models. One American consultant, who helps Eastern European countries assess Russian options and does not want his name used, says, "The Russians are definitely up to snuff, and it's nice to be able to say that."

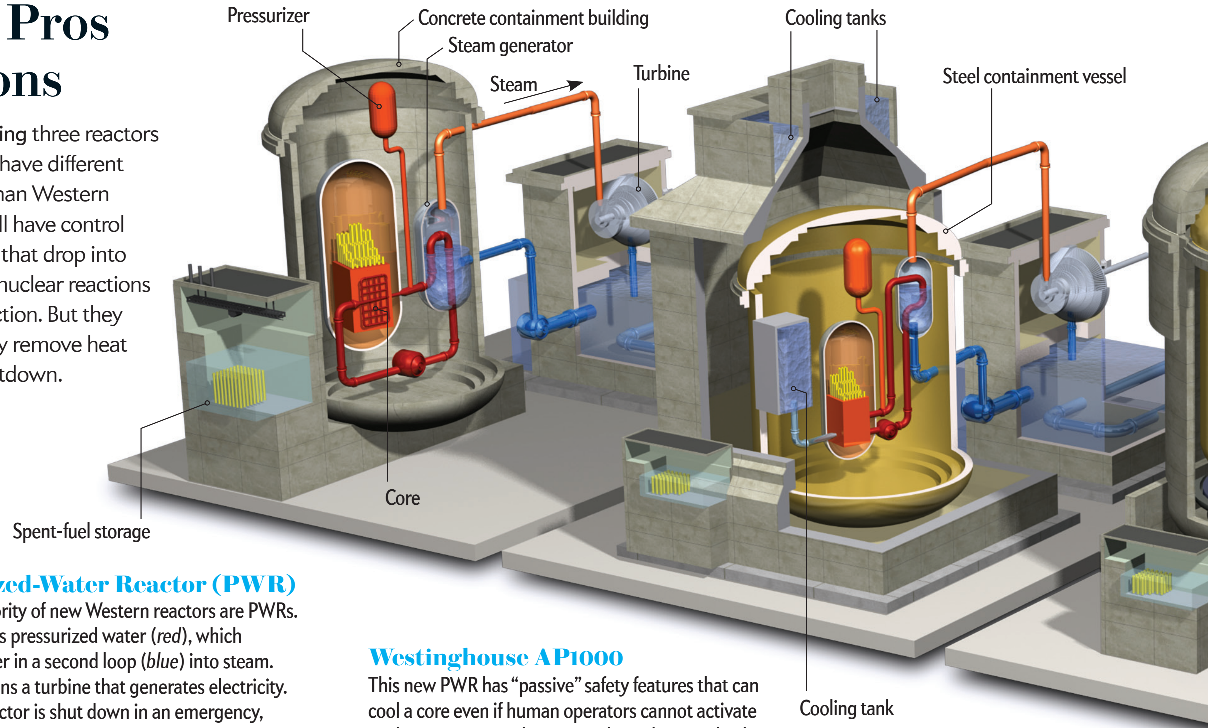
Good design does not preclude the possibility of bad construction, however. "There are still lingering concerns over the quality of their manufacturing of parts and components, construction quality and vendor support in the longer term once the reactor is up and running," the consultant says. Bolshov counters that Rosatom is watching those issues carefully: "Rosatom has made serious investments to have competition among manufacturers for better quality and price."

Another reason the VVERs are considered safe is a feature meant to prevent a Chernobyl-style accident. In the days after Chernobyl exploded, the Soviet Union tasked Bolshov, then a working physicist, with somehow figuring out how to contain Chernobyl's melting reactor core. He devised a makeshift platform of snakelike pipes cooled with water, covered with a thin graphite layer and stuffed between two one-meter-thick concrete layers. "It was done as a sandwich," Bolshov says. Heroic coal miners dug underneath the fuming reactor and inserted the platform to "catch" the molten core before it sunk into the earth and hit the water table.

In the end, Bolshov's creation did not have to fight the sinking core, which solidified just two meters short of the sandwich. Yet the close call paved the road for Russia's modern "core catchers": bowl-shaped vessels cooled by water and made

Safety Pros and Cons

Russia is promoting three reactors (*red names*) that have different safety features than Western designs (*blue*). All have control rods (*not shown*) that drop into the core to stop nuclear reactions during a malfunction. But they differ in how they remove heat to prevent a meltdown.



Pressurized-Water Reactor (PWR)
The vast majority of new Western reactors are PWRs. The core heats pressurized water (*red*), which converts water in a second loop (*blue*) into steam. The steam spins a turbine that generates electricity. When the reactor is shut down in an emergency, the pressurized water cools the core. If electricity is lost, pumps cannot circulate the water and a meltdown could occur, so backup power is essential.

Westinghouse AP1000
This new PWR has "passive" safety features that can cool a core even if human operators cannot activate cooling systems or electricity is lost. The main backup consists of tanks that need only gravity to continually flood the core with cooling water for several days.

of steel, iron and aluminum oxides, built directly under all of Russia's new pressurized-water reactors. Core catchers are already buried 4.5 meters below the two VVER-1200s going up in southern Russia.

Russia views the core catcher as vital. France's Areva design also includes one. Some experts have argued that core catchers would not have made a difference at Fukushima. But several of the plant's reactor cores "slumped" into the concrete underneath, as von Hippel describes it, prompting him to conclude: "A core catcher is a good idea."

M.I.T.'s Hanson and others argue, though, that the larger goal of safety engineers should be minimizing possible damage so much that core catchers are superfluous. "The public and the reactor owners will never buy the argument that a reactor is safe because it has a core catcher. Once the core is destroyed, the reactor is a total waste, and controlling the molten material after the fact does not eliminate off-site doses" of radiation, Hanson says. Westinghouse has adopted that approach; spokesperson Scott Shaw says the company's new AP1000 does not need a core catcher. If the core were to begin melting, an operator could flood the space around the reactor vessel with water held in tanks, for up to 72 hours.

PROLIFERATION OF WORRY

ROSATOM'S VVER PLANTS come with another innovation, one related to cash. The company will build Turkey's first reactors—four VVER-1200s—under a unique "build-own-operate" deal akin to a 60-year rental. It is the first time the arrangement has been used for a nuclear plant anywhere in the world, but Rosatom hopes the arrangement will catch on. "This is very attractive for newcomers," Rosatom's Novikov says.

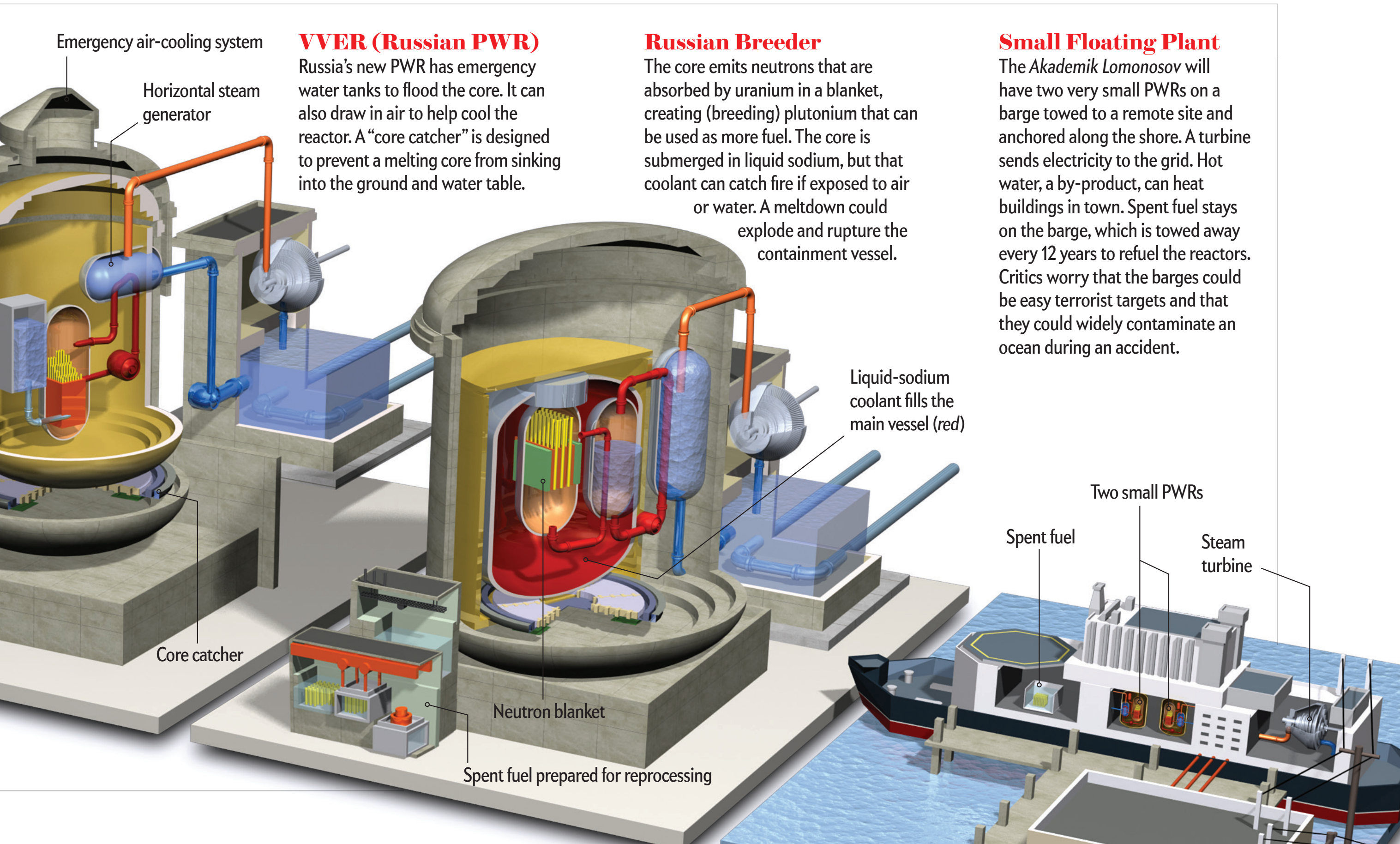
This rental plan, yet another part of Russia's effort to widen access to nuclear technology, worries proliferation watchers, particularly when it comes to the Middle East. Russia has completed Iran's only reactor, a VVER-1000, and has trained Iranian technicians in nuclear energy. The West fears that Iran is using its knowledge to develop clandestine weapons.

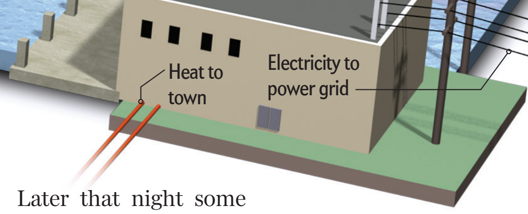
"It's hard not to look at the interest in civilian nuclear reactors in Turkey and other countries in the region as part of a hedging strategy," says Eric Edelman, former U.S. ambassador to Turkey. Although nuclear reactors are a far cry from nuclear weapons, expertise in nuclear technology and access to the nuclear fuel cycle, he says, "still opens the door for a more proliferated Middle East." Henry Sokolski, executive director of the Washington, D.C.–based Nonproliferation Policy Education Center, agrees that training could potentially be used for nefarious purposes. "I don't care how proliferation-proof the hardware is—the training isn't."

Some naysayers also claim that reactors could be run to generate plutonium. Yet "plutonium from a pressurized-water reactor is isotopically wrong for bombs," says Robert Kelley, a former program manager for nuclear intelligence at Los Alamos National Laboratory and a former International Atomic Energy Agency inspector. "It doesn't bother me in the slightest that Russia is selling pressurized-water reactors." The real problem, he says, would be with enriching or reprocessing nuclear fuel, ramping it up to weapons-grade material.

By agreeing to take back and perma-

Illustration by Don Foley





nently store nuclear waste, "Russia is providing something very worthwhile from a nonproliferation perspective," von Hippel says. And "the Russians are good at keeping in compliance with regulations," says Hanson, who leads an M.I.T. program on the developing world's desire for nuclear energy. He would rather see worrisome nations opt for Russia's one-stop-shopping approach to nuclear development than conduct nuclear projects on their own.

THE NEXT GENERATION ... OF PEOPLE

WHETHER RUSSIAN TRAINING of foreign nuclear workers raises concern or not, it is vital to preventing reactor accidents, many of which are caused in whole or in part by human-operator error. "Even small reactors require training people up in a big, big way," Sokolski says.

Russia has been training newcomers in Obninsk, a two-hour drive from Moscow. New dorms and classrooms are being added here to old ones to handle a flood of foreigners expected in the coming years. Far from home, the first of some 600 Turkish students who will study here—baby-faced and hopeful—sip tea and look to their bright futures as their country's first nuclear workers.

"Thank God there's Skype" to break the tedium, 21-year-old Gökçehan Tosun says in a coffee shop near her dorm. Next to her is Olgun Köse, practicing his English, a relief after months of grueling Russian lessons. "We've seen much cold, we've seen minus 35 degrees," he says, his eyes widening at the memory of his first Russian winter. Yet with guaranteed careers and good salaries ahead, they are the envy of their friends.

Later that night some of the Turks will play in a band, Rockkuyu, after Turkey's Akkuyu nuclear project. Köse talks of how oil is "finished," how solar is too expensive, and how nuclear energy is green, "fast and beautiful." The students believe the new reactors will give Turkey, and themselves, entrée into a scientifically advanced and sustainable future. "Turkey will grow up," Köse says.

And Russia will be right there to help them. SA

MORE TO EXPLORE

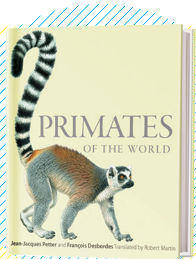
Tracking Nuclear Proliferation within a Commercial Power Program. Susan Voss. Nonproliferation Policy Education Center, August 2012. http://bit.ly/144h1HI

Russia's Nuclear Renaissance. Eve Conant. Pulitzer Center on Crisis Reporting, 2012–2013. http://bit.ly/SmCOEu

Rosatom's English-language Web site: www.rosatom.ru/en

World Nuclear Association's Russia Web page: http://bit.ly/1bNtbxH

SCIENTIFIC AMERICAN ONLINE
To download apps that track Russia's reactors, go to ScientificAmerican.com/oct2013/conant

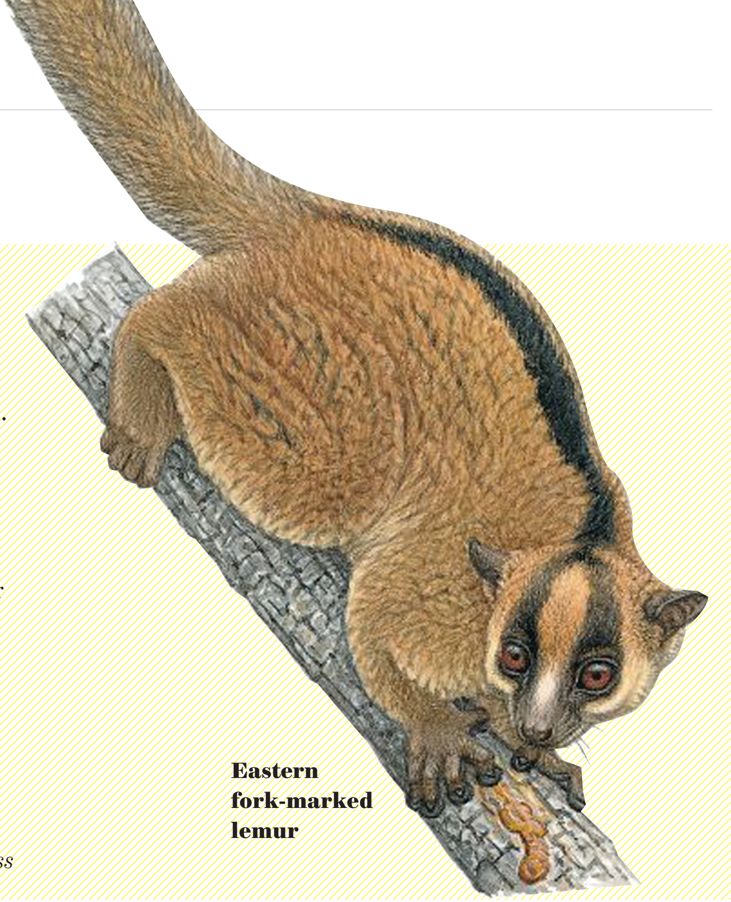


Primates of the World

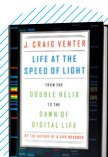
by Jean-Jacques Petter and François Desbordes. Translated by Robert Martin. Princeton University Press, 2013 ($29.95)

Woolly monkeys, rotund yet agile primates of South America, look plump because of their thick fur, which is the densest possessed by any primate. Muriqui spider monkeys are also known as hippie monkeys for their tendency to hug one another in times of stress. In infancy, bearded saki monkeys use their prehensile tails as a "fifth hand" but lose that grasping ability as they mature. These are but a few of the delightfully surprising facts peppered through this beautifully illustrated tour of the lives and behaviors of our closest living relatives in the animal kingdom.

—Arielle Duhaime-Ross



Eastern fork-marked lemur



Life at the Speed of Light: From the Double Helix to the Dawn of Digital Life

by J. Craig Venter. Viking, 2013 ($26.95)

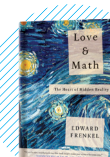
Venter, the scientist famed for his role in sequencing the human genome, opens this remarkable book with his answer to a question that lies at the heart of biology: "What is life?" Life, he asserts, is wholly reducible to the "DNA machines" and "protein robots" that operate within cells, and he hopes to prove it by constructing organisms entirely from scratch. After presenting a concise, deeply informed summary of the science surrounding synthetic biology, Venter makes clear that he has little time for excessive ethical hand-wringing about "playing God," writing that "my greatest fear is not the abuse of technology but that we will not use it at all." To that end, he details an ambitious vision for a future in which custom-made organisms heal the planet, unlock life's origins and extend humanity's reach beyond Earth.

Five Billion Years of Solitude: The Search for Life among the Stars

by Lee Billings. Current, 2013 ($27.95)

Exoplanets get all the headlines these days, but most planet hunters will tell you that the search for Earth-like worlds orbiting distant stars is just a step in the age-old quest to learn whether or not we are alone in the universe. In his compelling, wide-ranging survey, Billings steps back to look at this broader picture, largely through richly textured portraits of some of the giants of the field, including Frank Drake, inventor of SETI; Geoff Marcy, the world's most accomplished planet hunter; Jim Kasting, who literally wrote the book on what makes a world habitable; and Sara Seager, whose thinking is firmly rooted in the exoplanetology of the future. That's just the smallest sampling, however, of where Billings's extraordinary tale of scientific discovery will take you.

—Michael Lemonick



Love and Math: The Heart of Hidden Reality

by Edward Frenkel. Basic Books, 2013 ($27.99)

Like many adolescent males, young Frenkel had a one-track mind. He scaled fences, cut classes and arranged furtive rendezvous, all for his "secret lover"—abstract, high-level mathematics. Institutional anti-Semitism in the Soviet Union blocked his enrollment at Moscow State University, so he sought out informal advisers, snuck into lectures and devoured mathematical literature. Eventually Frenkel landed at Harvard University; he is now a professor at the University of California, Berkeley. Part ode, part autobiography, *Love and Math* is an admirable attempt to lay bare the beauty of numbers for all to see, even though some readers may balk at Frenkel's mentions of Kac-Moody algebras and of objects called hyperspheres.

—John Matson

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For more recommendations, go to ScientificAmerican.com/oct2013/recommended

ILLUSTRATION BY FRANÇOIS DESBORDES, *PRIMATES OF THE WORLD*, 2013

Michael Shermer is publisher of *Skeptic* magazine (www.skeptic.com). His book *The Believing Brain* is now out in paperback. Follow him on Twitter @michaelshermer

When Science Doesn't Support Beliefs

Then ideology needs to give way

Ever since college I have been a libertarian—socially liberal and fiscally conservative. I believe in individual liberty and personal responsibility. I also believe in science as the greatest instrument ever devised for understanding the world. So what happens when these two principles are in conflict? My libertarian beliefs have not always served me well. Like most people who hold strong ideological convictions, I find that, too often, my beliefs trump the scientific facts. This is called motivated reasoning, in which our brain reasons our way to supporting what we want to be true. Knowing about the existence of motivated reasoning, however, can help us overcome it when it is at odds with evidence.

Take gun control. I always accepted the libertarian position of minimum regulation in the sale and use of firearms because I placed guns under the beneficial rubric of minimal restrictions on individuals. Then I read the science on guns and homicides, suicides and accidental shootings (summarized in my May column) and realized that the freedom for me to swing my arms ends at your nose. The libertarian belief in the rule of law and a potent police and military to protect our rights won't work if the citizens of a nation are better armed but have no training and few restraints. Although the data to convince me that we need some gun-control measures were there all along, I had ignored them because they didn't fit my creed. In several recent debates with economist John R. Lott, Jr., author of *More Guns, Less Crime,* I saw a reflection of my former self in the cherry picking and data mining of studies to suit ideological convictions. We all do it, and when the science is complicated, the confirmation bias (a type of motivated reasoning) that directs the mind to seek and find confirming facts and ignore disconfirming evidence kicks in.

My libertarianism also once clouded my analysis of climate change. I was a longtime skeptic, mainly because it seemed to me that liberals were exaggerating the case for global warming as a kind of secular millenarianism—an environmental apocalypse requiring drastic government action to save us from doomsday through countless regulations that would handcuff the economy and restrain capitalism, which I hold to be the greatest enemy of poverty. Then I went to the primary scientific literature on climate and discovered that there is convergent evidence from multiple lines of inquiry that global warming is real and human-caused: temperatures increasing, glaciers melting, Arctic ice vanishing, Antarctic ice cap shrinking, sea-level rise corresponding with the amount of melting ice and thermal expansion, carbon dioxide touching the level of 400 parts per million (the highest in at least 800,000 years and the fastest increase ever), and the confirmed prediction that if anthropogenic global warming is real the stratosphere and upper troposphere should cool while the lower troposphere should warm, which is the case.

The clash between scientific facts and ideologies was on display at the 2013 FreedomFest conference in Las Vegas—the largest gathering of libertarians in the world—where I participated in two debates, one on gun control and the other on climate change. I love FreedomFest because it supercharges my belief engine. But this year I was so discouraged by the rampant denial of science that I wanted to turn in my libertarian membership card. At the gun-control debate (as in my debates with Lott around the country), proposing even modest measures that would have almost no effect on freedom—such as background checks—brought on opprobrium as if I had burned a copy of the U.S. Constitution on stage. In the climate debate, when I showed that between 90 and 98 percent of climate scientists accept anthropogenic global warming, someone shouted, "LIAR!" and stormed out of the room.

Liberals and conservatives are motivated reasoners, too, of course, and not all libertarians deny science, but all of us are subject to the psychological forces at play when it comes to choosing between facts and beliefs when they do not mesh. In the long run, it is better to understand the way the world really is rather than how we would like it to be. SA

SCIENTIFIC AMERICAN ONLINE
Comment on this article at ScientificAmerican.com/oct2013

Illustration by Victo Ngai

The ongoing search for fundamental farces

Steve Mirsky has been writing the Anti Gravity column since a typical tectonic plate was about 34 inches from its current location. He also hosts the *Scientific American* podcast Science Talk.

Bouillabaisse Biology

Ladling out the latest about life's origin

This is probably going to come as a shock, which may strike you as kind of funny in a moment, but "soup had its greatest moment in 1953." That claim, outrageous to anyone who has recently enjoyed a really great bowl of bean-with-bacon, comes from British science journalist Adam Rutherford in his new book *Creation: How Science Is Reinventing Life Itself.*

A closer read, however, reveals that Rutherford is referring to the so-called prebiotic soup, a phrase coined by another eminent Englishman, evolutionary biologist J.B.S. Haldane, to describe the idea of a pond rich enough in chemical ingredients to allow the spontaneous formation of the first living cell.

American chemist Stanley Miller reached the aforementioned pinnacle of soup in 1953 when he combined water, methane, hydrogen and ammonia, which he assumed were the primary constituents of the atmosphere some four billion years ago, and zapped it with electricity to emulate lightning. (I told you "shock" would be retroactively funny.) Within days the mixture darkened. Miller's analysis revealed the presence of amino acids, top-notch prebiotic material.

This seemingly obvious proof of concept for how the early Earth got lousy with biochemistry became so famous that it was later featured in the final episode of *Star Trek: The Next Generation*. The omnipotent being known as Q drags our hero Captain Picard to Earth some 3.5 billion years ago, notes some bubbling slime and says, "This is you. I'm serious. Right here, life is about to form on this planet for the very first time. A group of amino acids are [sic] about to combine to form the first protein, the building blocks of what you call life … everything you know, your entire civilization—it all begins right here in this little pond of goo." The scene is worth watching just to witness actor John de Lancie's attempt to turn "goo" into a three-syllable word.

The problem with the bisque-beginning-of-life concept is that it's almost certainly wrong. Prebiotic soup, Rutherford told me by phone from across the big pond, "was this incredible idea that complexity, in terms of biomolecules, can spontaneously emerge if the conditions are right. It is iconic, and it's an important experiment. But it's also been a great contributor to what I argue is the incorrect version of how life started on this planet."

The amino acids generated in a Miller-style primordial ooze just lie there, not doing the backstroke. "Once those chemicals have reacted," Rutherford says, "they will stop reacting. That's the end of that process. And that's the one fundamental thing that life doesn't do. Life is a continual chemical reaction." You could wait forever and still not get a fly in your soup.

Researchers more recently have identified places that better fit the bill for bringing about the birds and bees: deep-sea hydrothermal vents called white smokers. But a white smoker's heat, like Stan's electricity, only does so much to a given pot of soup. The smokers also bring up lots of hydrogen, however, and force cell-size pores into the surrounding molten rock. Strip away an electron from one of the hydrogen atoms spewing from these vents, and you're left with a lonely proton. And a proton imbalance on either side of one of these pores necessarily leads to a flow of charged particles that just maybe gets enough chemistry going—and keeps it going—to lead to us pondering torpid ponds today.

"Life is like a casino," Rutherford says, and not because they're good places to find white smokers, in this case coughing up their retirement savings. "Everyone knows that in the long run the house always wins. But what life is is a kind of continual breaking even against the house. And it's been continual for about four billion years. When you die, you get kicked out, and the energy contained within your cells gets returned to the house. But during your life you extract energy from the environment and hang onto it. It's sort of like sitting at the blackjack table and managing to stay there for the whole night." Before you leave, don't forget to catch the show. SA

SCIENTIFIC AMERICAN ONLINE
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Illustration by Matt Collins

50, 100 & 150 Years Ago compiled by Daniel C. Schlenoff

Innovation and discovery as chronicled in *Scientific American*

October 1963

Stress and the Zulu

"A study of high blood pressure among Zulus in the Union of South Africa by Norman A. Scotch of the Harvard University School of Public Health reports that hypertension, or high blood pressure, was significantly more prevalent among the urban Zulus than those on a rural 'reserve.' Scotch first attributed this to the greater severity and variety of stress in the location, where the predictable strains of city life and detribalization are complicated by the stressful effects of apartheid, the South African policy of strict separation of the races. In general, however, Scotch believes that urbanization may not be stressful in itself. 'It is not simply a case of change but rather of success or failure in change.' The individuals most likely to be hypertensive were 'those who maintained traditional cultural practices and who were thus unable to adapt successfully to the demands of urban living.'"

October 1913

Gas for Motorists

"With the advantages of automatic vending devices apparent, a Michigan company has placed on the market a gasoline vending slot machine for motorists. It is merely necessary for the person requiring gasoline to drop a fifty-cent piece in the slot, place the end of the flexible hose in his gasoline tank and turn the crank. Left to itself, it dispenses 200 gallons of fuel a week. Not only does the machine run without attention other than that required in filling the 'gas' tank, but it is capable of 'delivering the goods' any minute in the twenty-four hours and any driver who knows of its location has no need to awaken sleepy garage attendants in the middle of the night."

For a photograph album about motor vehicles in 1913, see www.ScientificAmerican.com/oct2013/motor-vehicles

Advancing Aviation

"The aviation meeting at Rheims, organized by the Aero Club de France, was held over the Aerodrome de la Champagne. The following seven makes actually took part in the competitions: Bréguet, Caudron and Goupey (biplanes); and Deperdussin, Morane-Saulnier, Nieuport, Ponnier (monoplanes). They are sufficiently representative to give an idea of the actual state of perfection the French aviation history has attained. The winner of the Coupe Internationale d'Aviation, otherwise known as the Gordon Bennett Cup, was Maurice Prévost, who

WINNING MACHINE: The Deperdussin airplane, with a 160-horsepower Gnôme motor, held the airspeed record in 1913.

SCIENTIFIC AMERICAN SUPPLEMENT, VOL. LXXVI, NO. 1973; OCTOBER 25, 1913

completed 200 kilometers at a speed of 200.803 kilometers per hour (124.5 miles per hour). The airplane is a Deperdussin monocoque, equipped with a 160-horsepower Gnôme motor [*see photograph*]."


Scientific American.

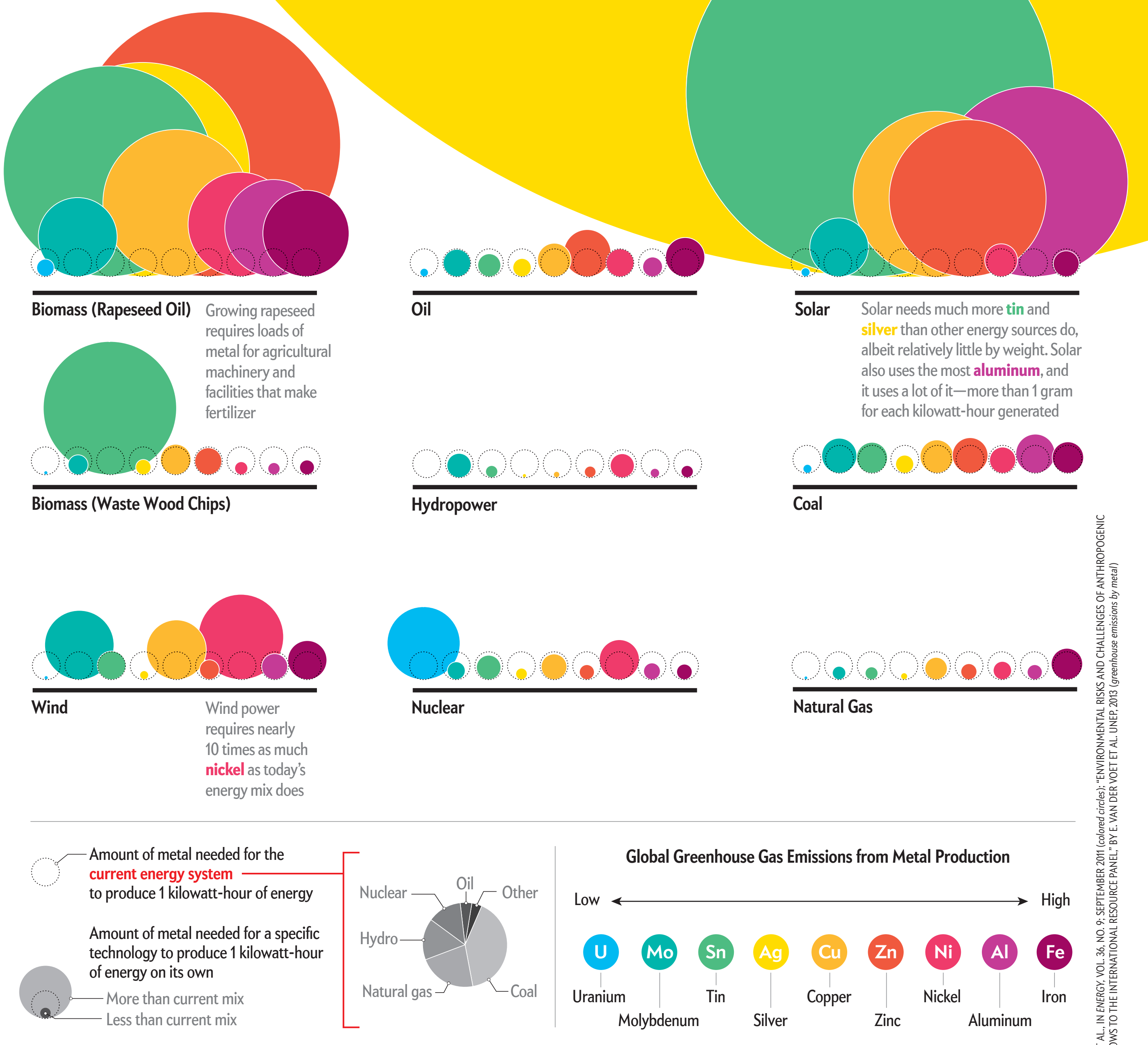
October
1863

New Metal: Indium

"A recent meeting of the Chemical Society of Union College reported the following notice of a new metal: 'Since the invention of the spectroscope in 1860, by a German chemist, Bunsen, several new chemical elements have, with its assistance, been discovered. In the summer of 1863, thallium having been detected in minute quantities in many of the products of the smelting works at Freiberg, Saxony, F. Reich and Th. Richter examined some of the ores, at the laboratories of the works, hoping to ascertain its source. These ores were prepared and examined before the spectroscope for thallium. No thallium line was found; but, instead, an indigo blue line, entirely new, and different from that produced by any known substance. Messrs. Reich and Richter pronounced it a new element, to which they gave the name of indium.'"

Hunting for Cedar

"In New Jersey there are men who make it a business to dig up the cedar trees buried for centuries in the swamps, and cut them into shingles of, it is said, extraordinary excellence. The New York *Post* says, 'These swamps are very valuable, an acre of such land commanding from five hundred to a thousand dollars. A peculiar feature of the swamps is that the soil is of purely vegetable growth, often twenty feet or more in depth. This peaty earth is constantly accumulating. Trees are found buried in it at all depths, quite down to solid ground. The deposit of timber is believed to be two thousand years old, and is all entirely sound.'"



Renewable Energy's Hidden Costs

Low-carbon power depends on climate-unfriendly metals

Because electricity and heat account for 41 percent of global carbon dioxide emissions, curbing climate change will require satisfying much of that demand with renewables rather than fossil fuels. But solar and wind come with their own up-front carbon costs. Photovoltaics require much more aluminum—for panel frames and other uses—than other technologies do, according to a 2011 study at Leiden University in the Netherlands. Alloys for wind turbines demand lots of nickel. Those metals are carbon culprits because they are produced in large amounts by high-energy extracting and refining processes.

The demand for metals, and their already significant carbon footprint, may grow with a switch to green energy. Given all the resources needed for new infrastructure, an analysis last year found that large solar installations take one to seven years to "break even" with coal power on the greenhouse scorecard. Wind farms take up to 12 years. All the more reason to make the switch sooner than later.

—John Matson

SCIENTIFIC AMERICAN ONLINE
For more on renewables, go to ScientificAmerican.com/oct2013/graphic-science

SOURCES: "METAL REQUIREMENTS OF LOW-CARBON POWER GENERATION," BY RENÉ KLEIJN ET AL., IN *ENERGY*, VOL. 36, NO. 9; SEPTEMBER 2011 (*colored circles*); "ENVIRONMENTAL RISKS AND CHALLENGES OF ANTHROPOGENIC METALS FLOWS AND CYCLES: A REPORT ON THE WORKING GROUP ON THE GLOBAL METAL FLOWS TO THE INTERNATIONAL RESOURCE PANEL," BY E. VAN DER VOET ET AL. UNEP, 2013 (*greenhouse emissions by metal*)

Graphic by Arno Ghelfi